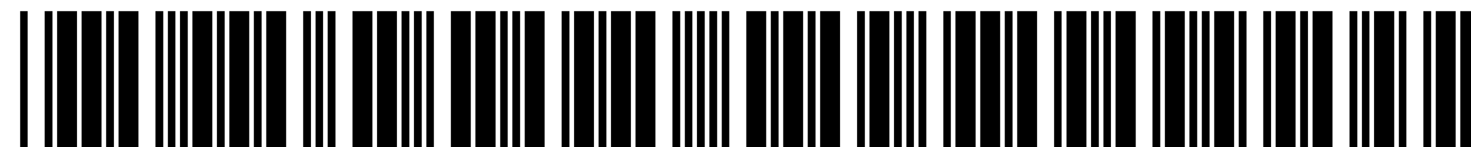

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Schmidt et al.

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(54) **ADJUSTING THE CHARGE CARRIER LIFETIME IN A BIPOLAR SEMICONDUCTOR DEVICE**

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(73) Assignee: **Infineon Technologies AG**, Neubiberg (DE)

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Jul. 28, 2015 (DE) 10 2015 112 265

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H01L 29/10 (2006.01)
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(58) **Field of Classification Search**
CPC B82Y 20/00; H01L 31/035236
USPC 257/21, 618, 44, 139; 438/138
See application file for complete search history.

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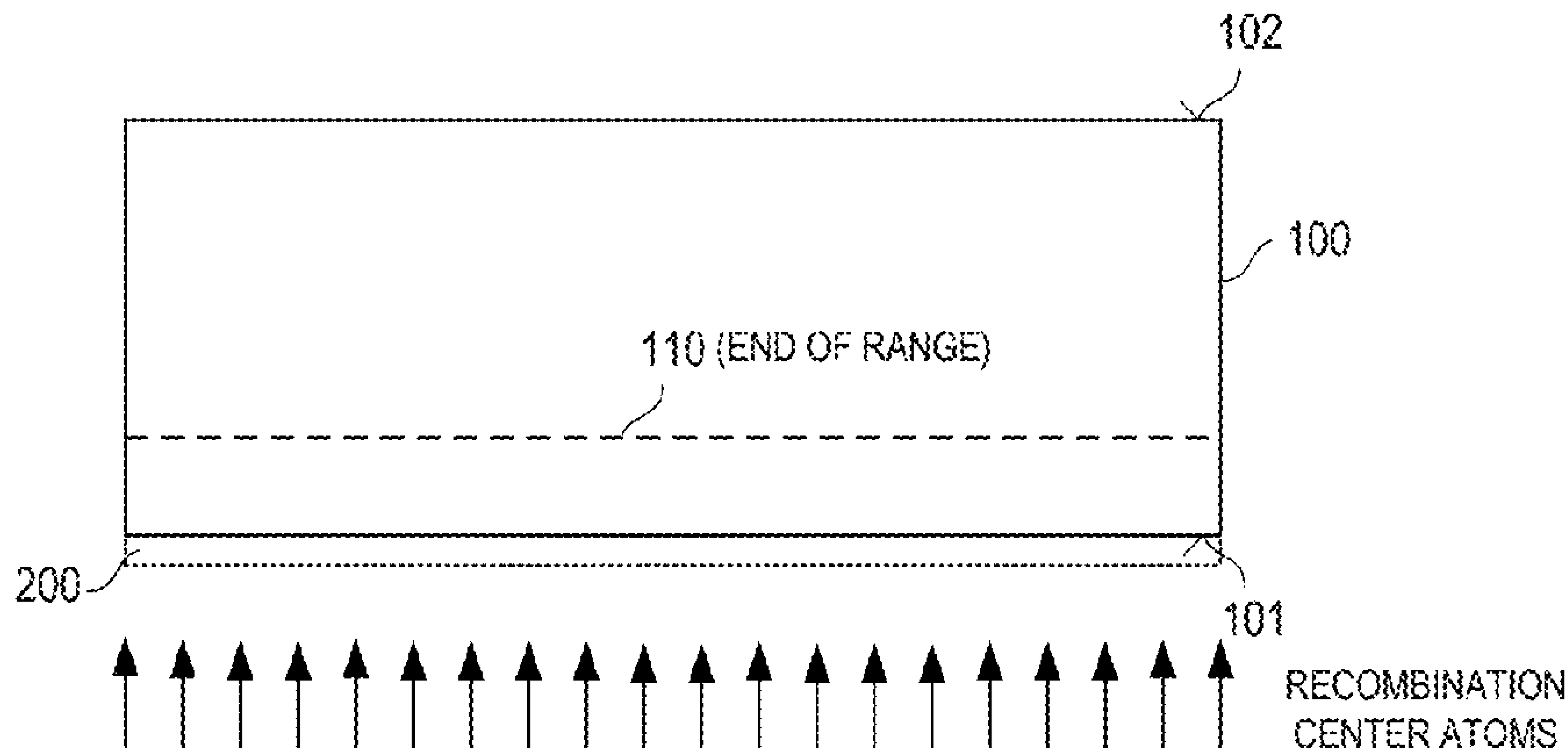
Primary Examiner — Jami M Valentine
(74) *Attorney, Agent, or Firm* — Murphy, Bilak & Homiller, PLLC

(57) **ABSTRACT**

Disclosed are a method and a semiconductor device. The method includes implanting recombination center atoms via a first surface into a semiconductor body, and causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process.

37 Claims, 9 Drawing Sheets



(51) **Int. Cl.**

H01L 29/66	(2006.01)
H01L 29/739	(2006.01)
H01L 29/08	(2006.01)
H01L 21/266	(2006.01)
H01L 21/225	(2006.01)
H01L 21/263	(2006.01)

(52) **U.S. Cl.**
CPC ***H01L 29/66325*** (2013.01); ***H01L 29/7393*** (2013.01)

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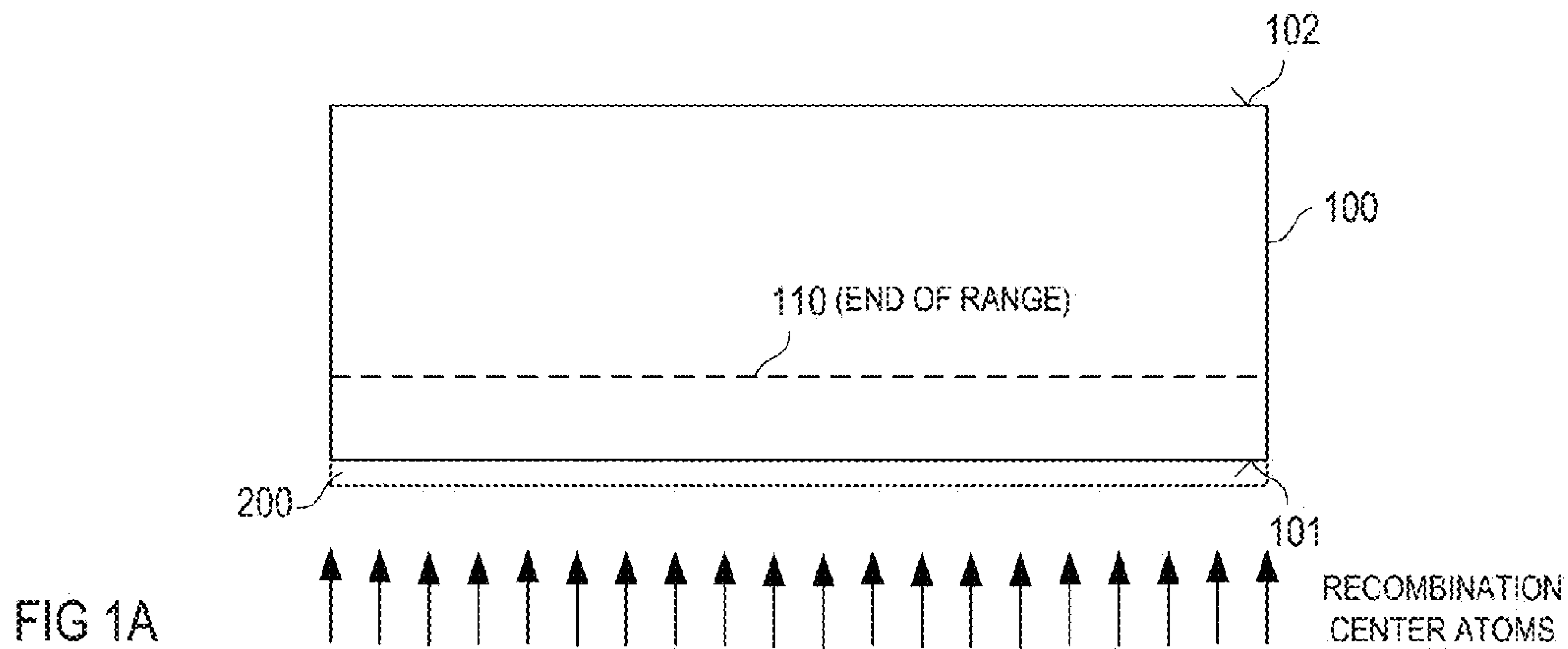

FIG 1A

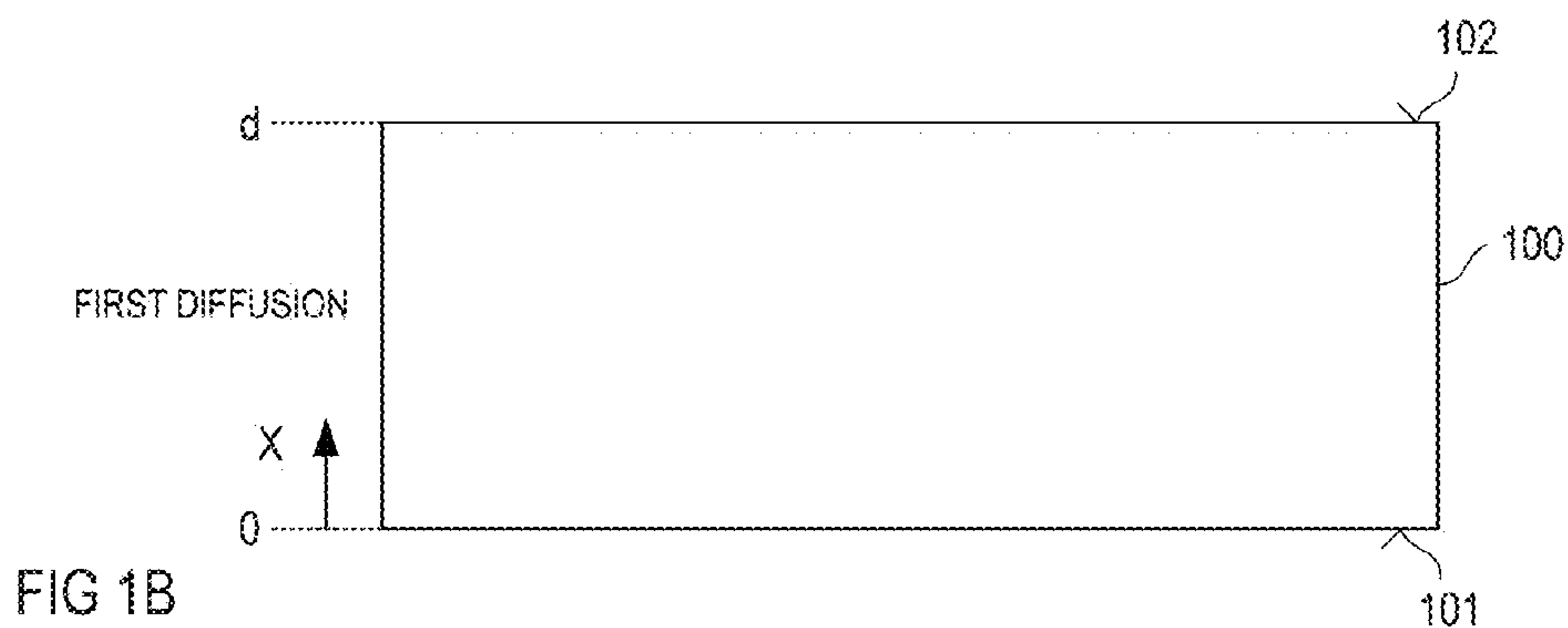

FIG 1B

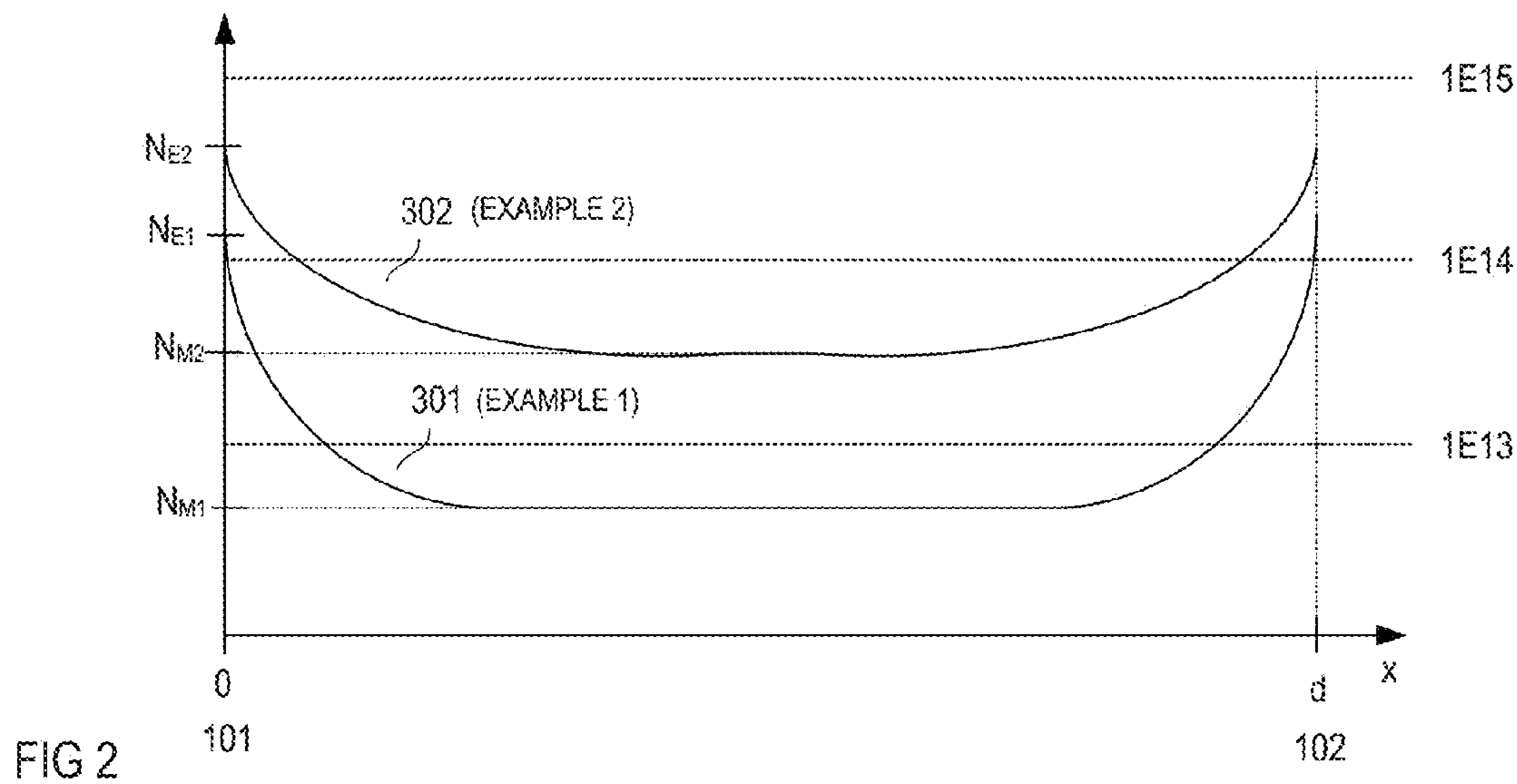

FIG 2

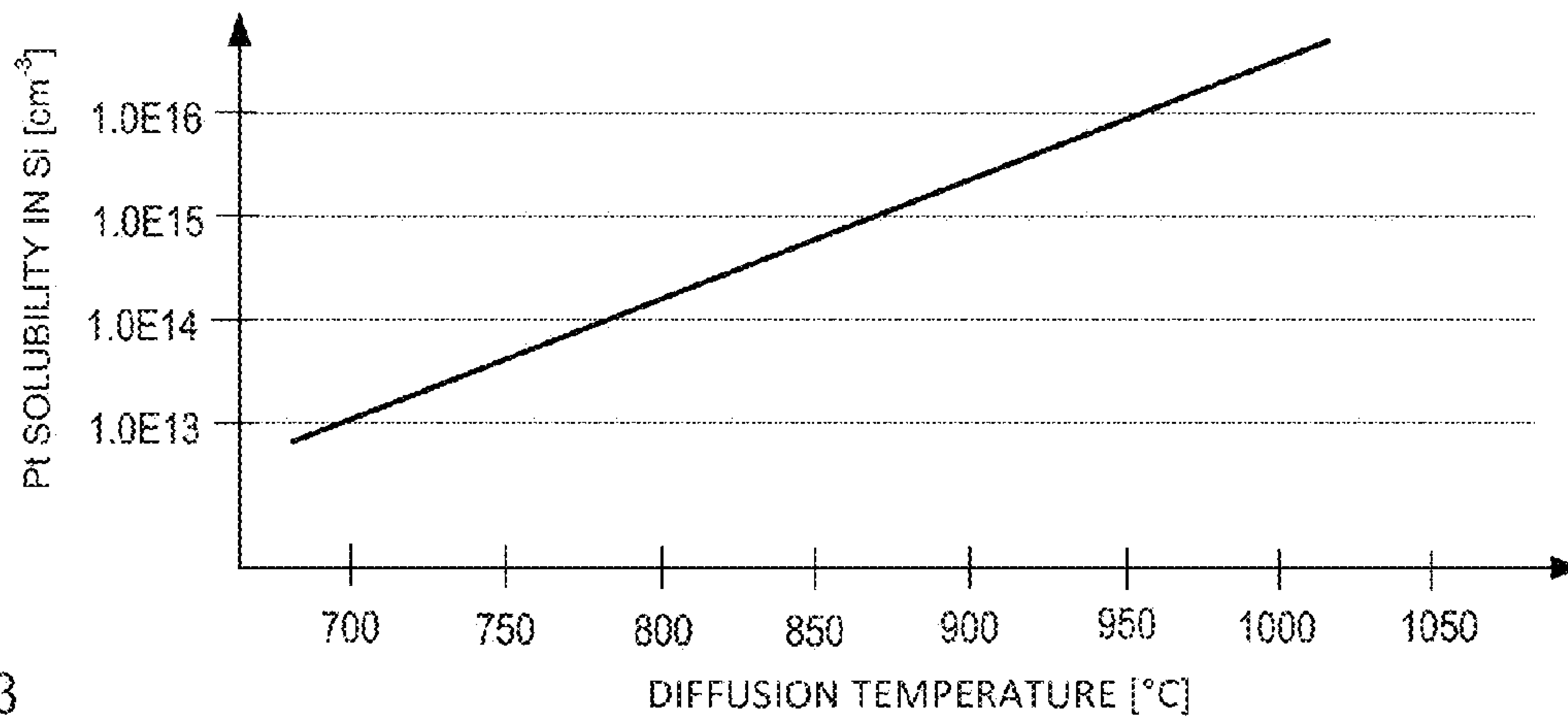

FIG 3

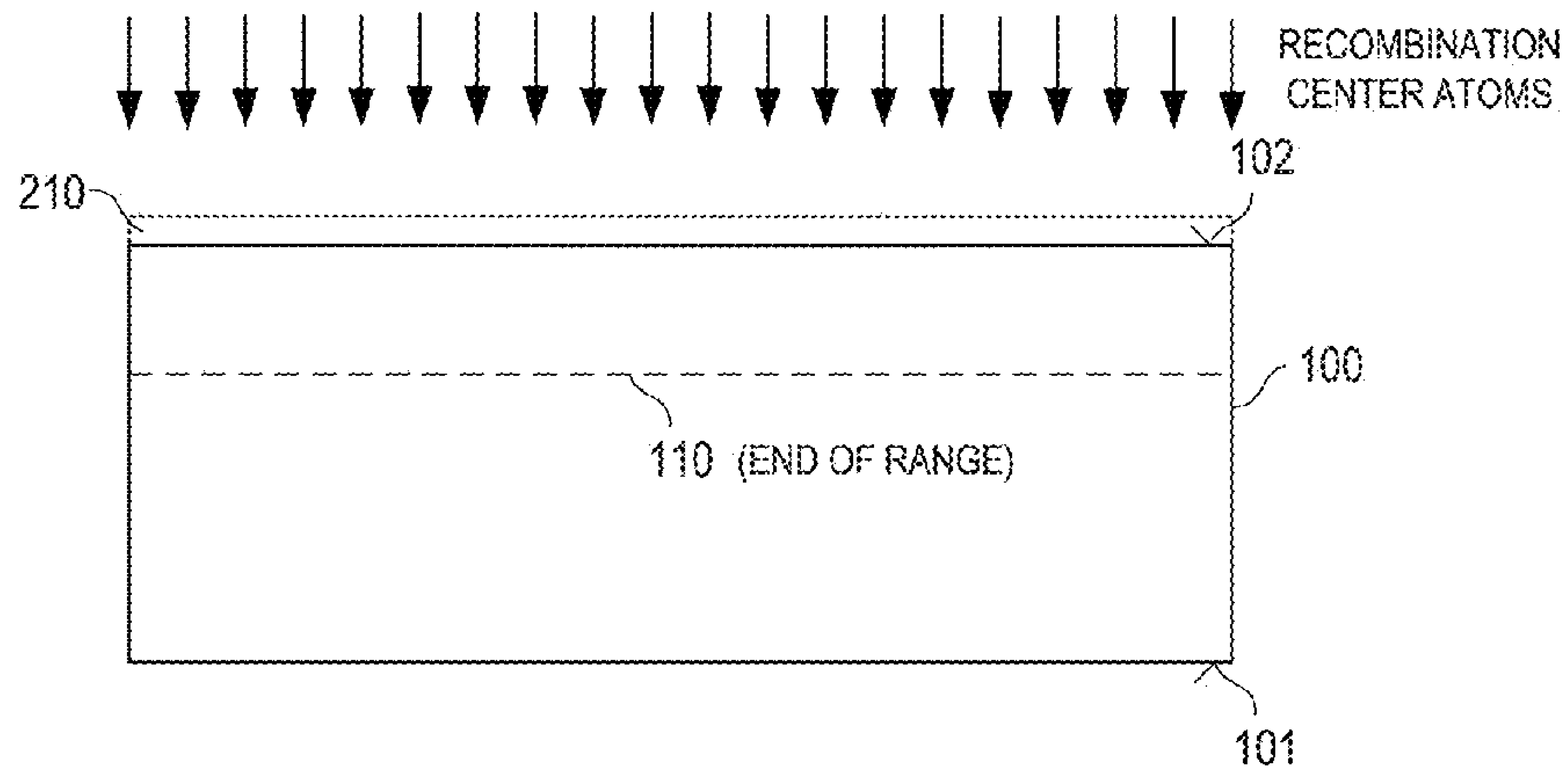

FIG 4

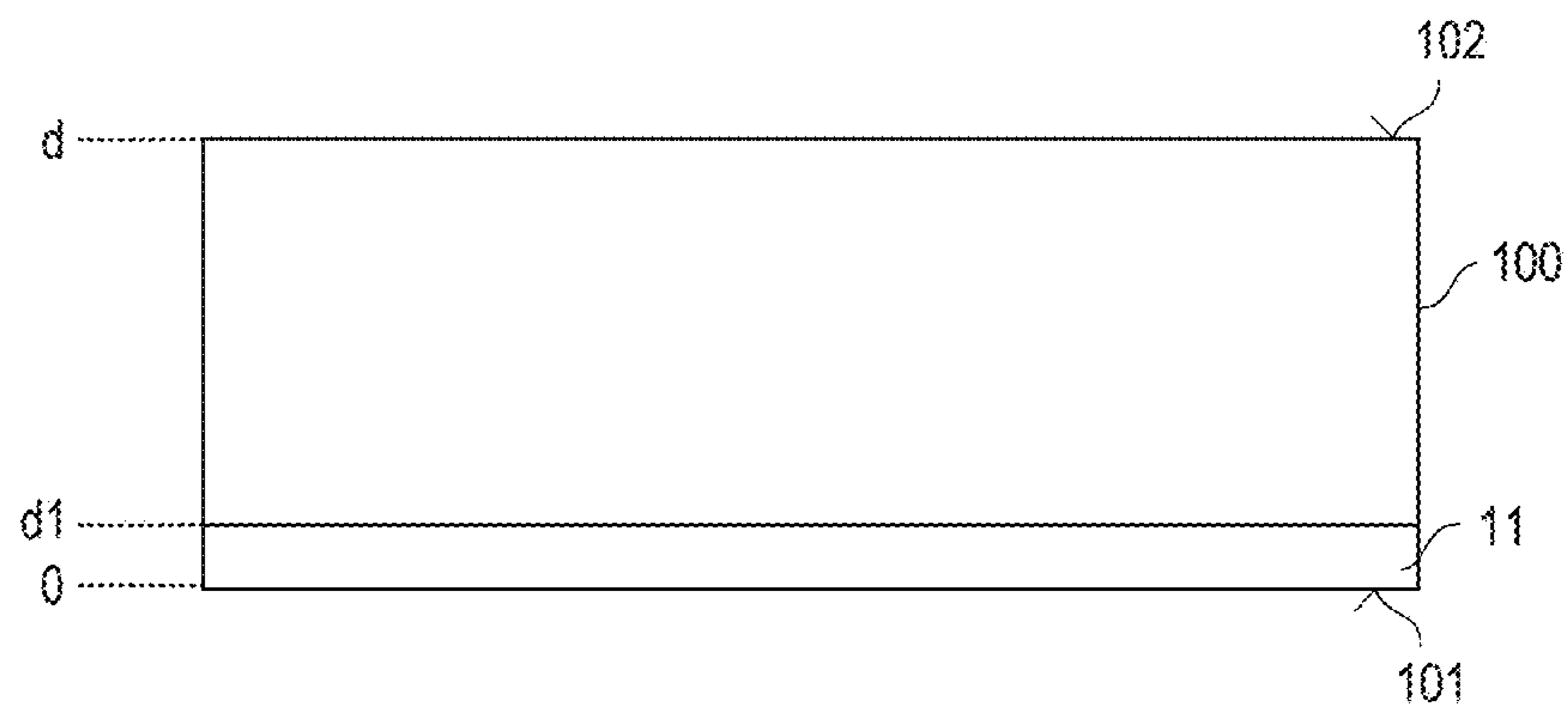

FIG 5A

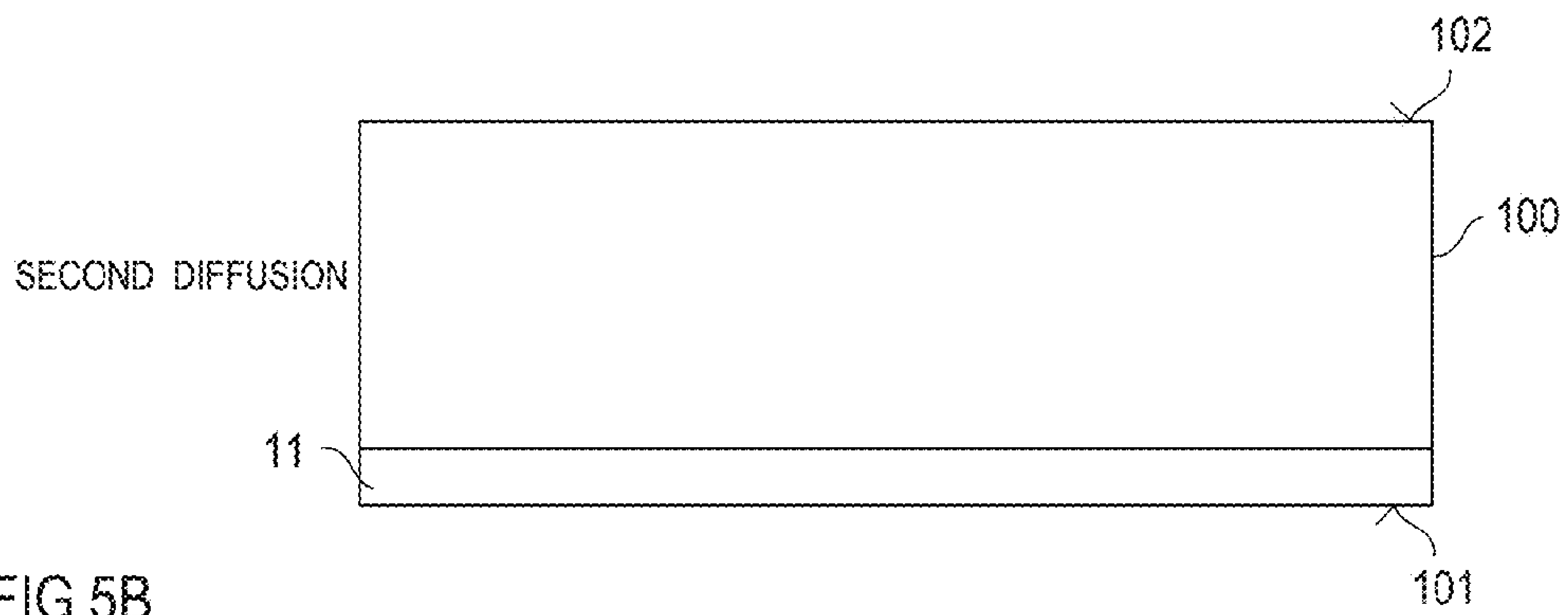

FIG 5B

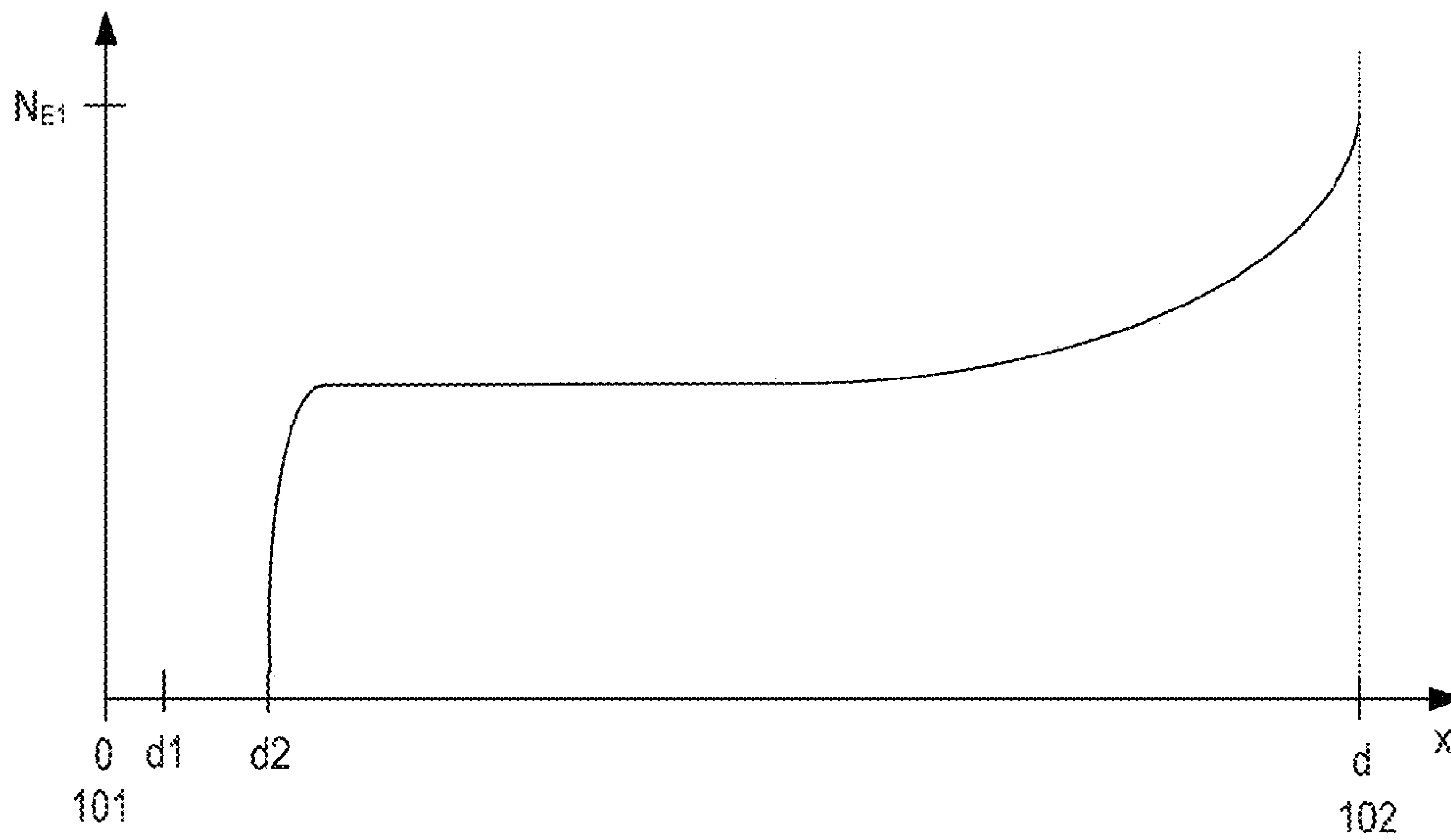

FIG 6

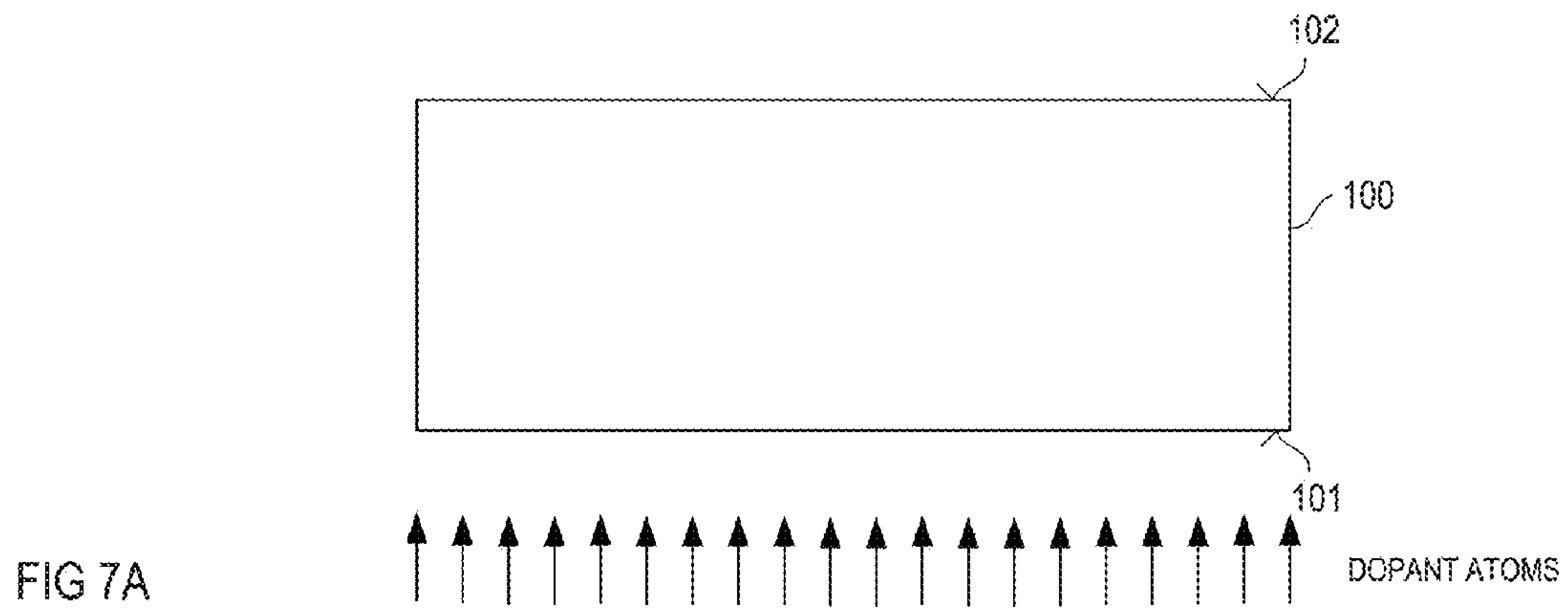

FIG 7A

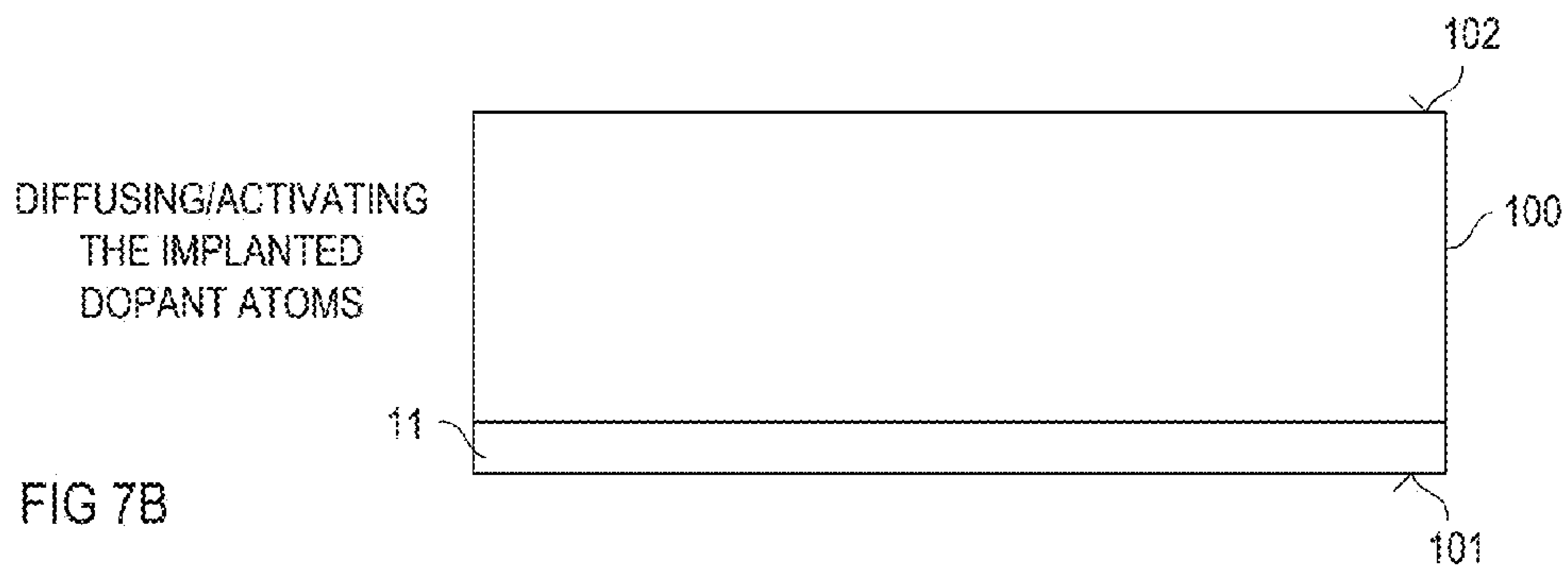

FIG 7B

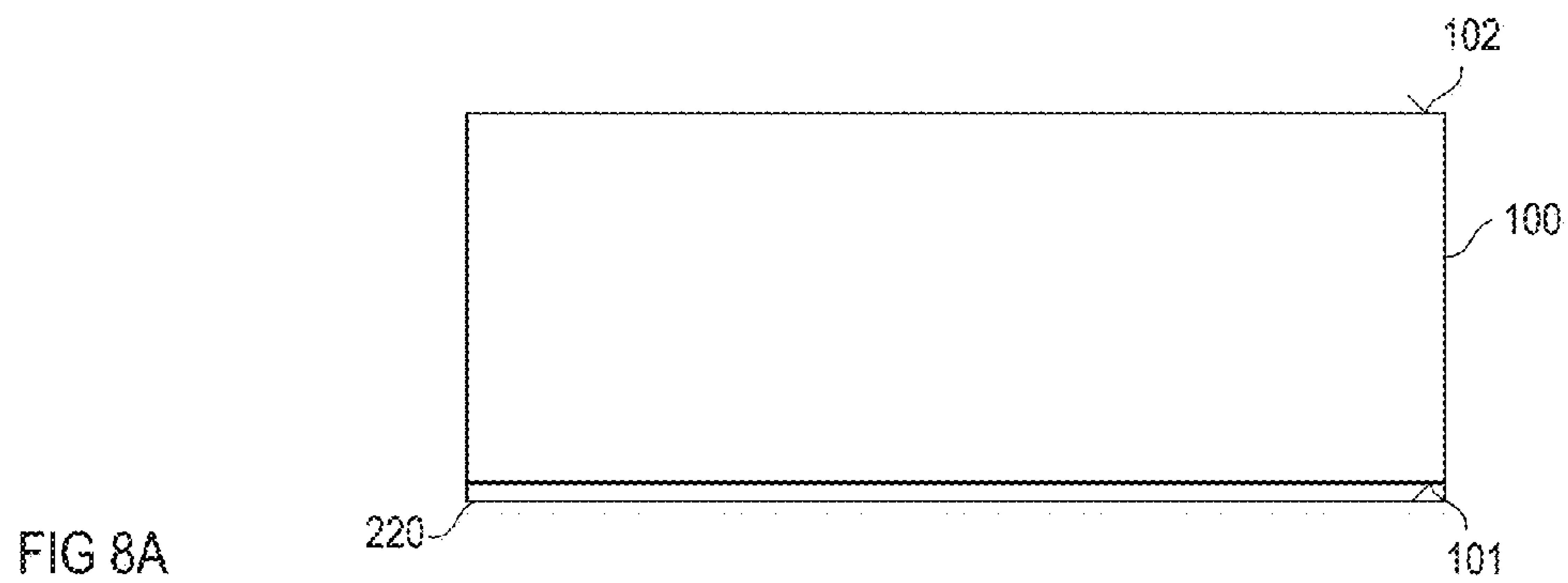

FIG 8A

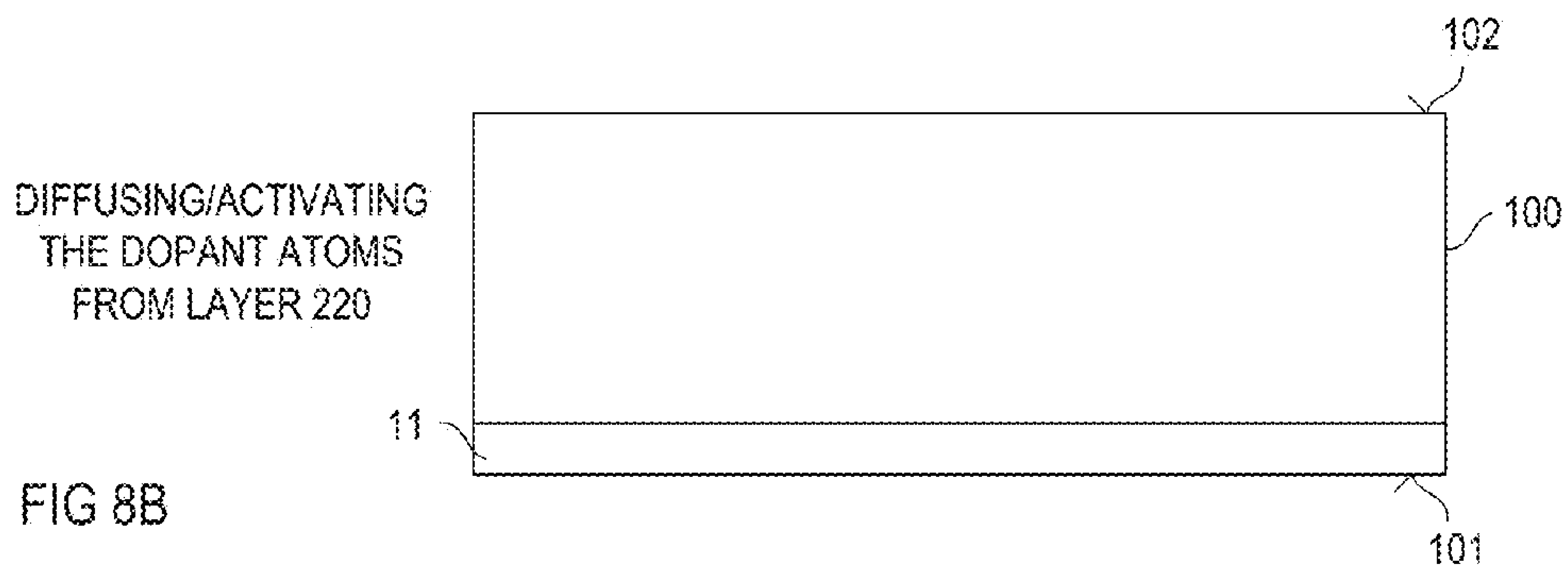

FIG 8B

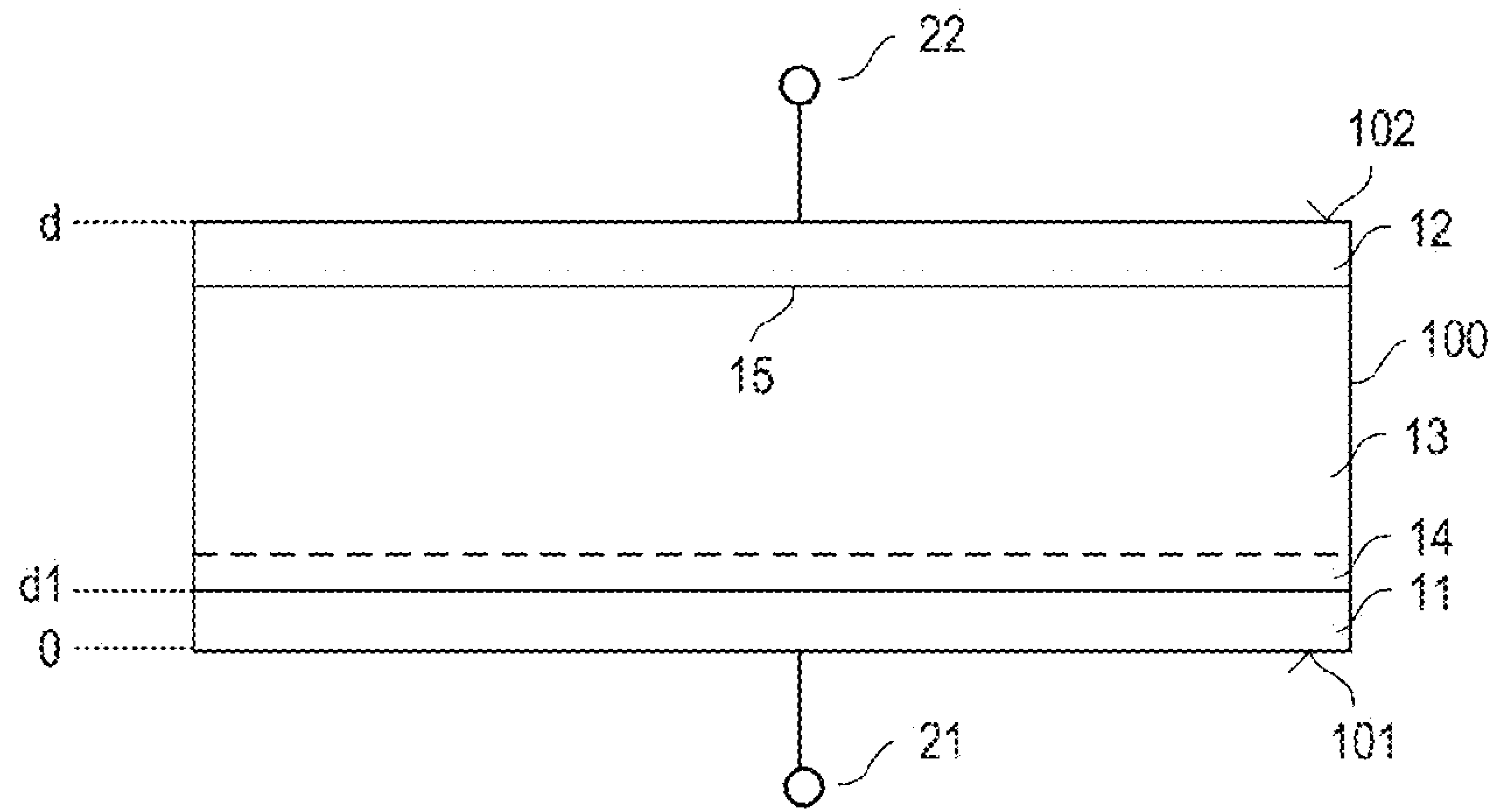

FIG 9

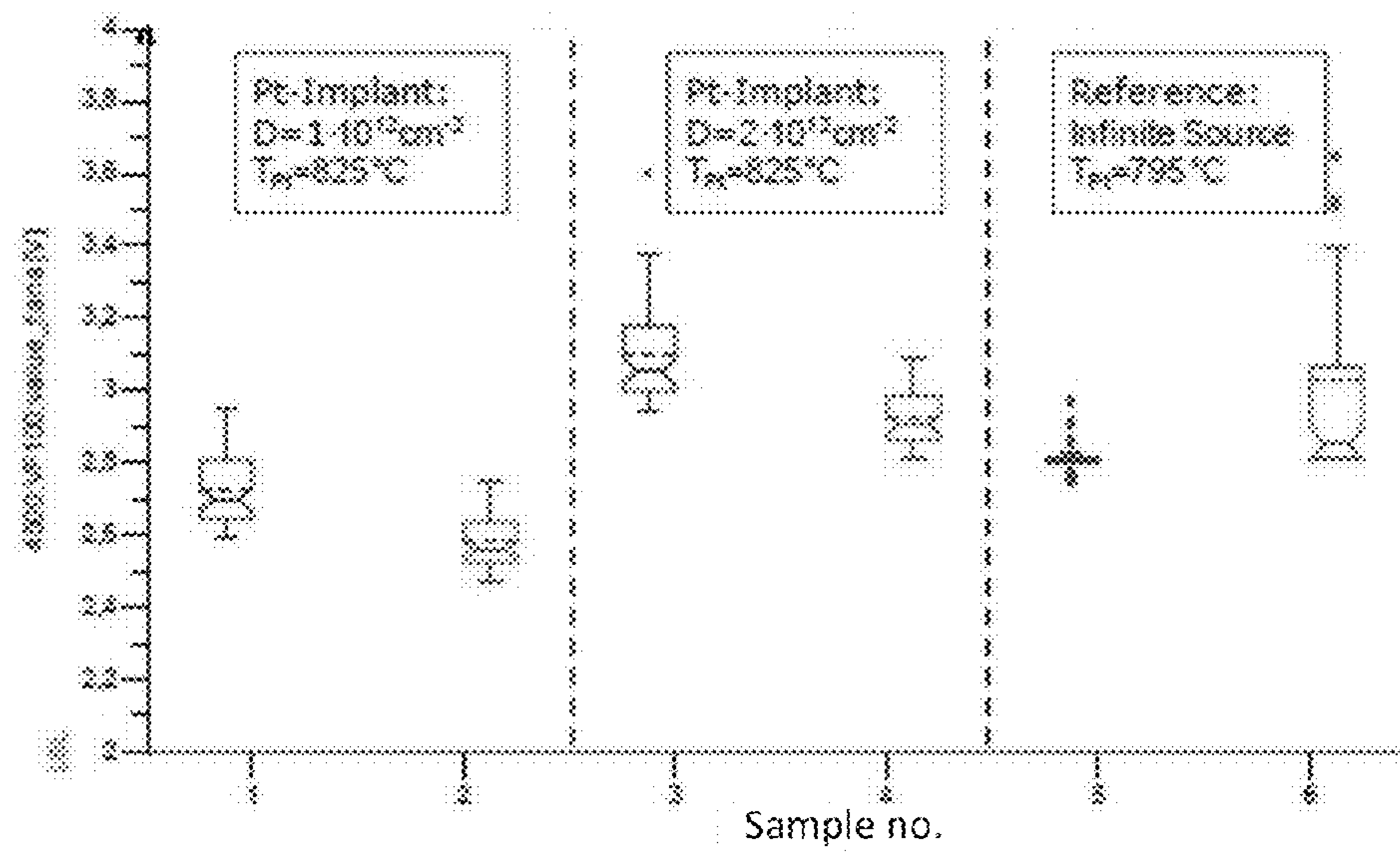

FIG 10

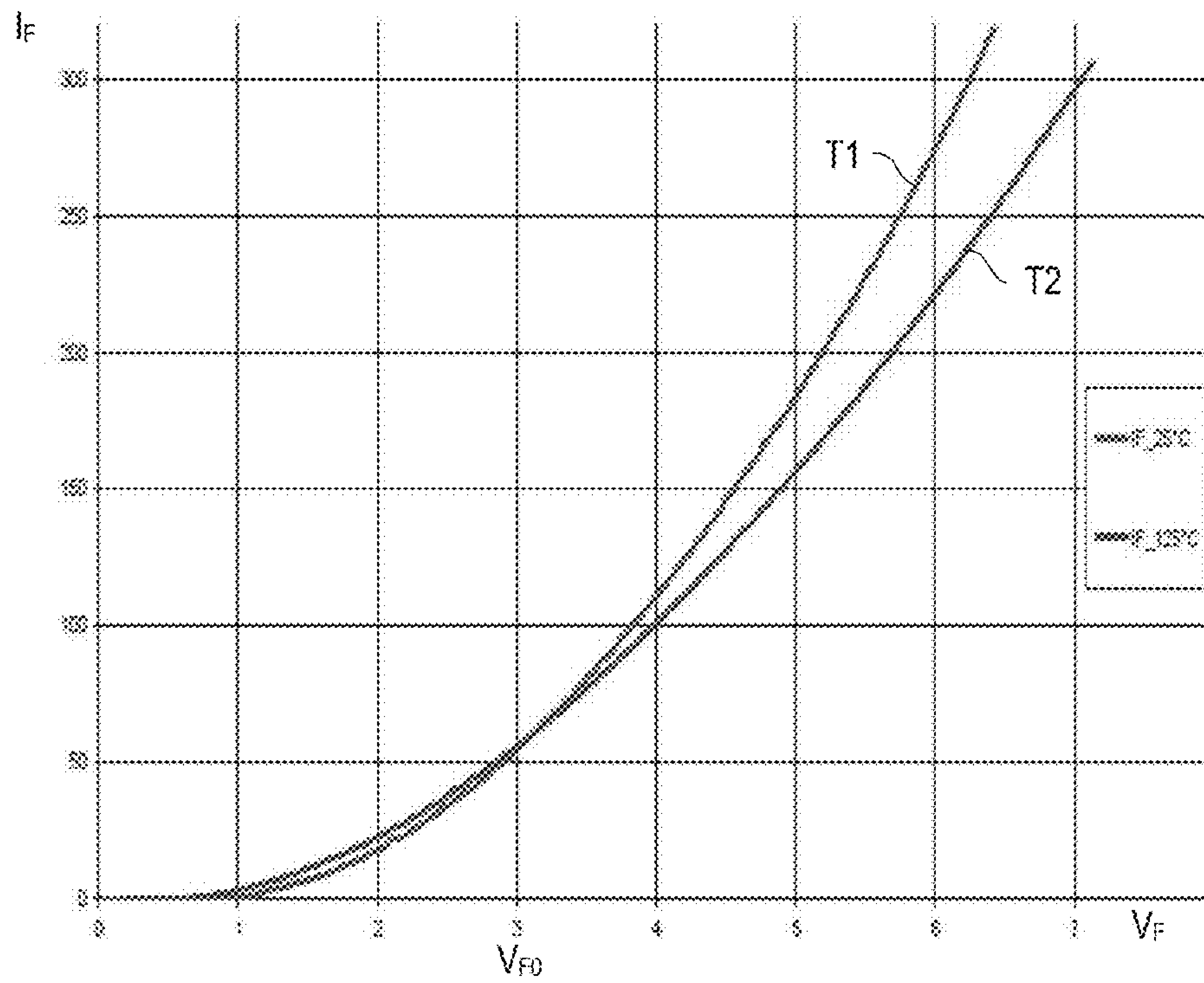

FIG 11

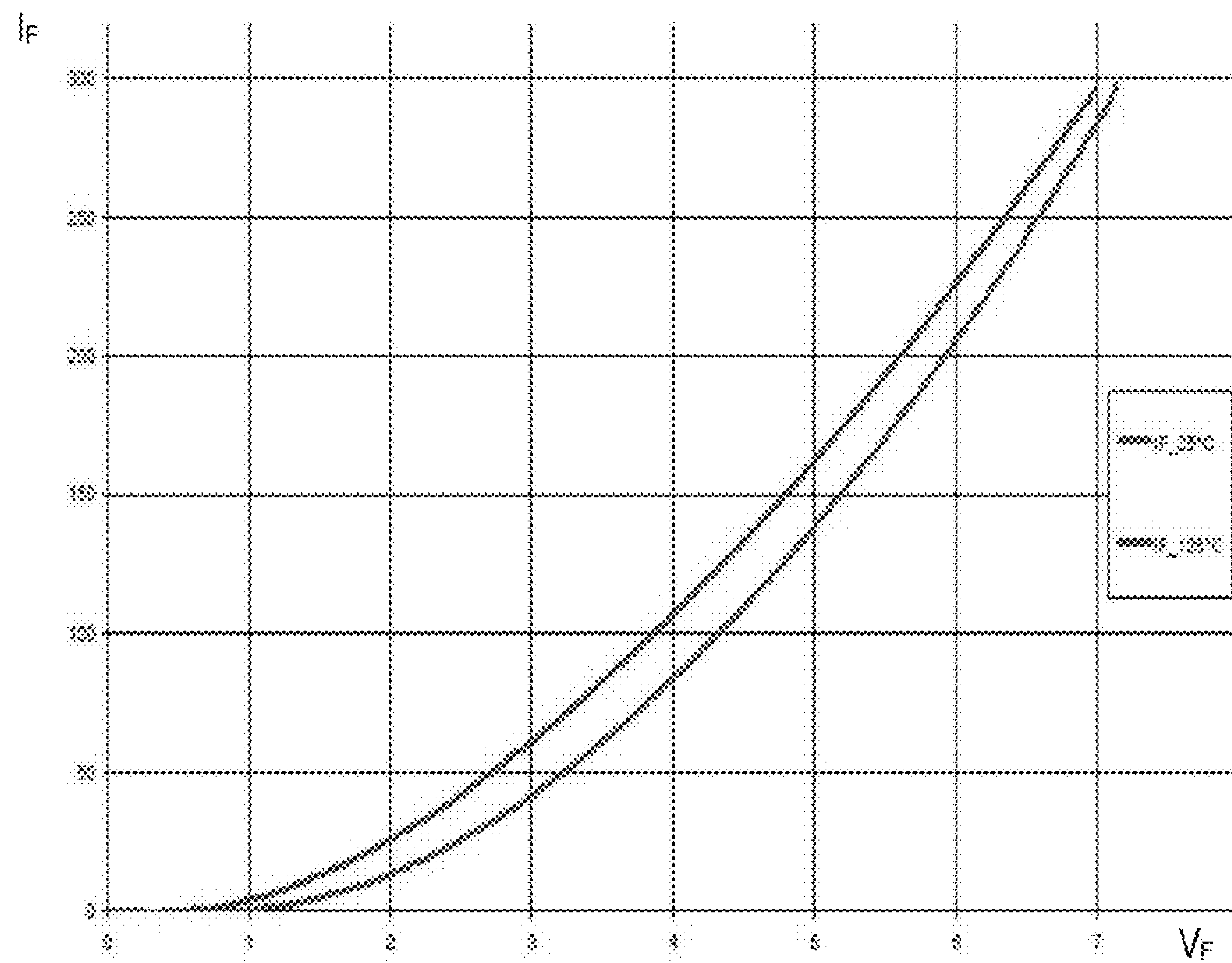

FIG 12

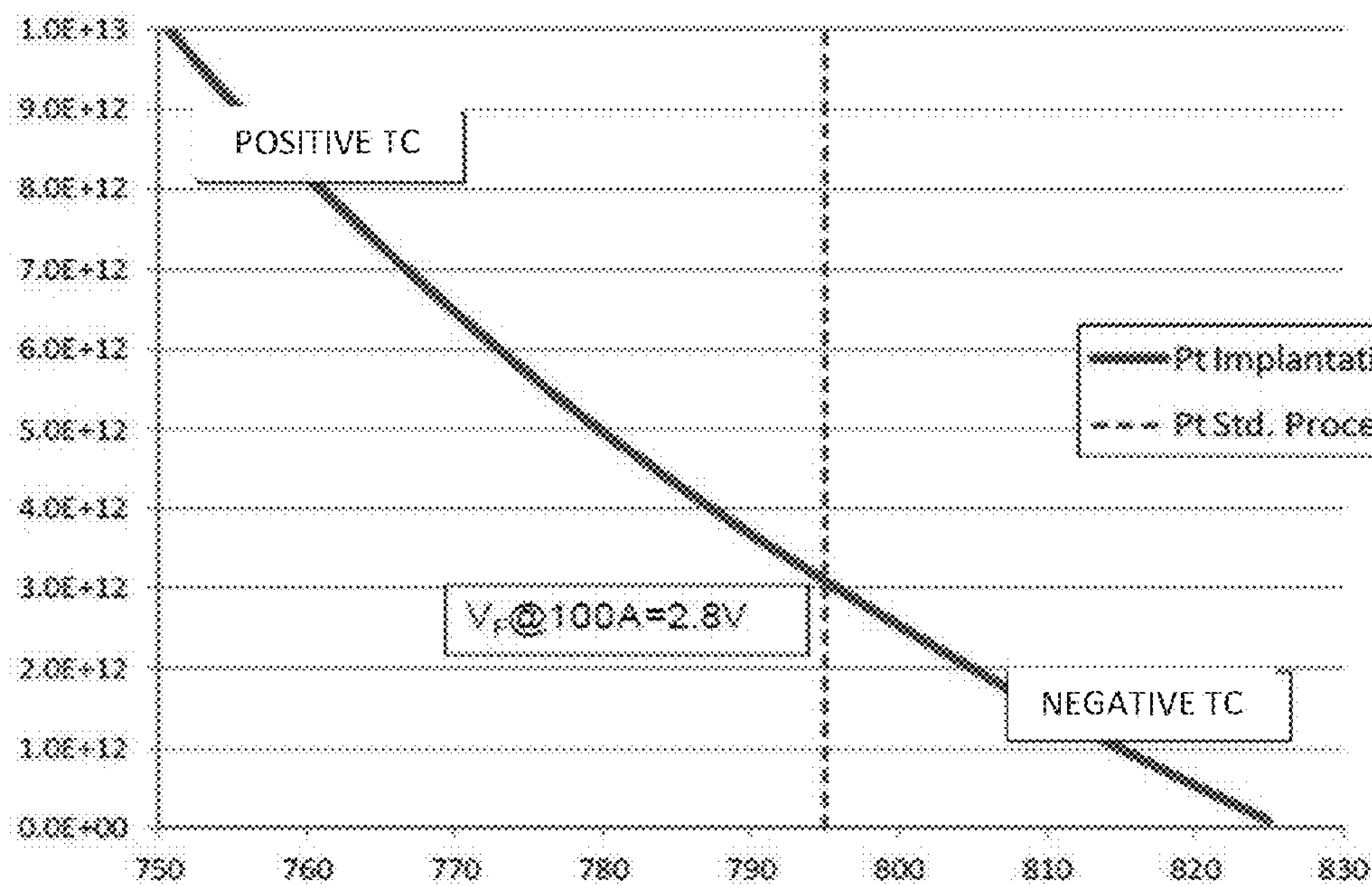

FIG 13

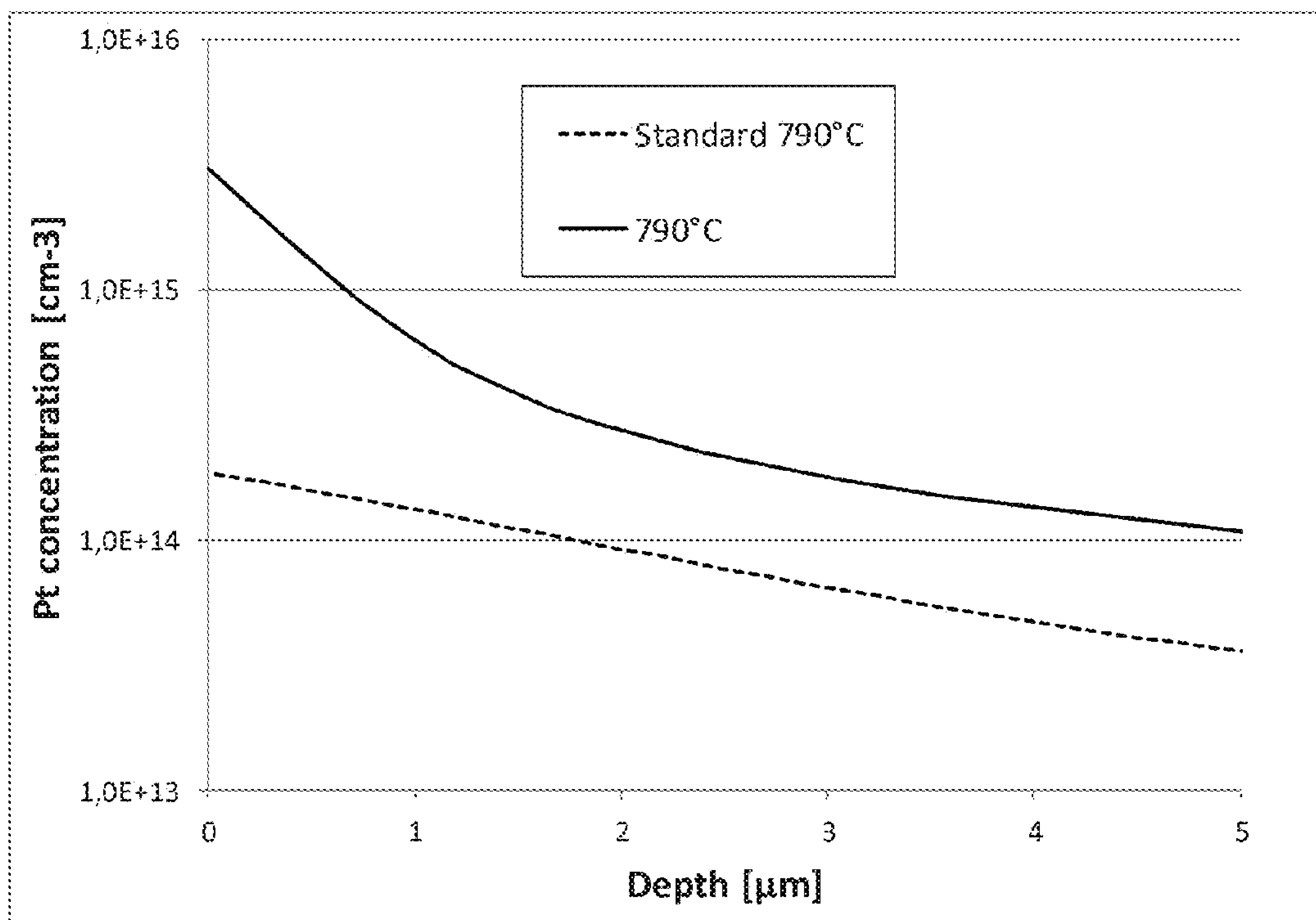

FIG 14

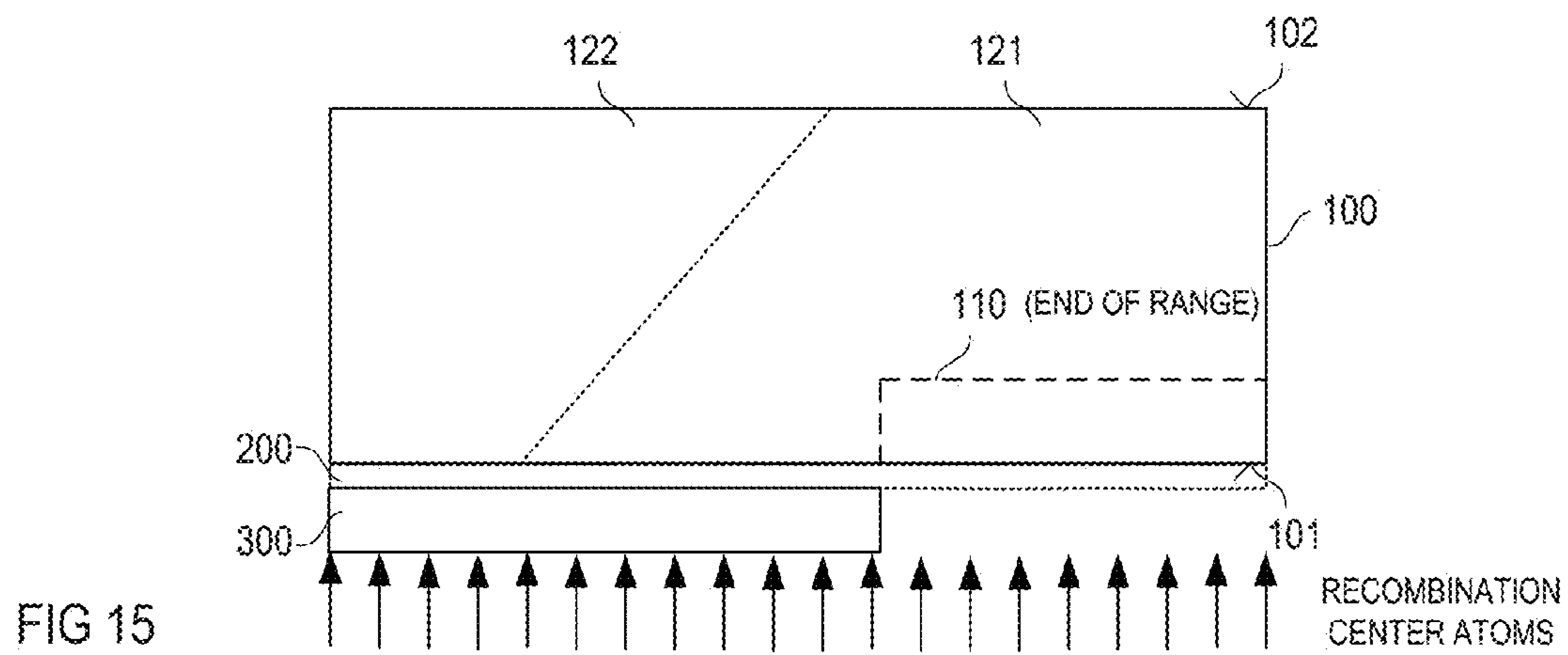

FIG 15

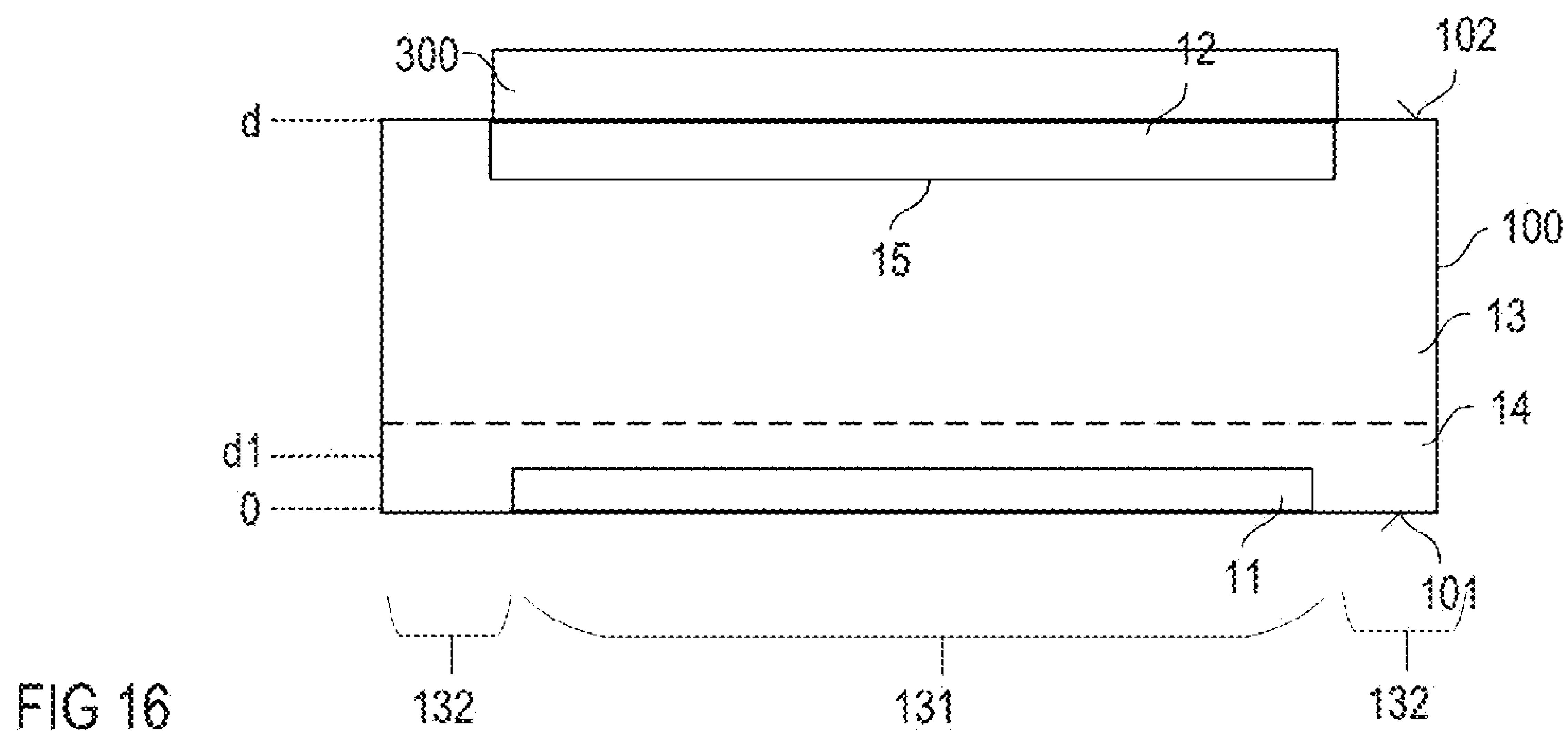

FIG 16

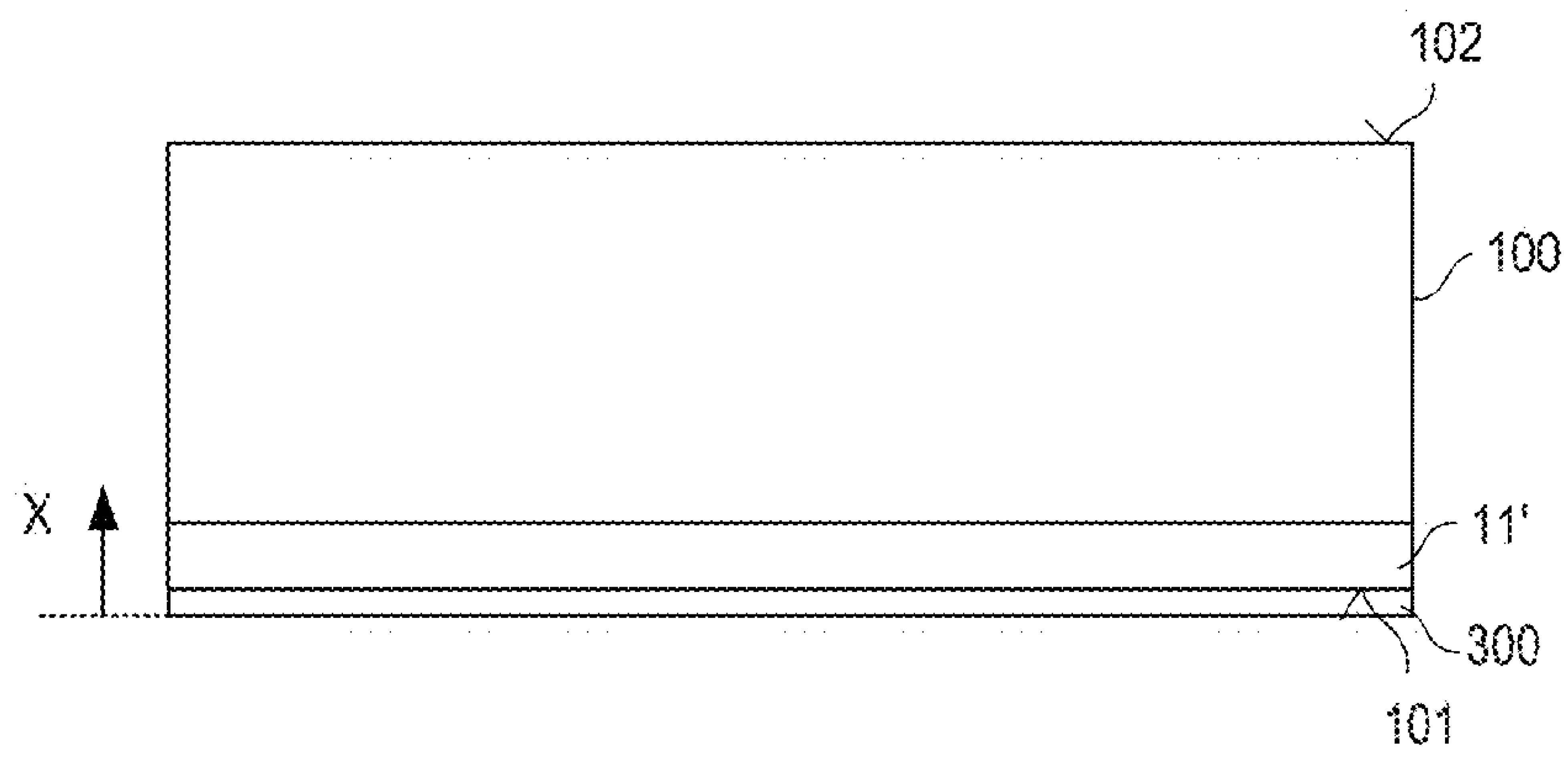

FIG 17

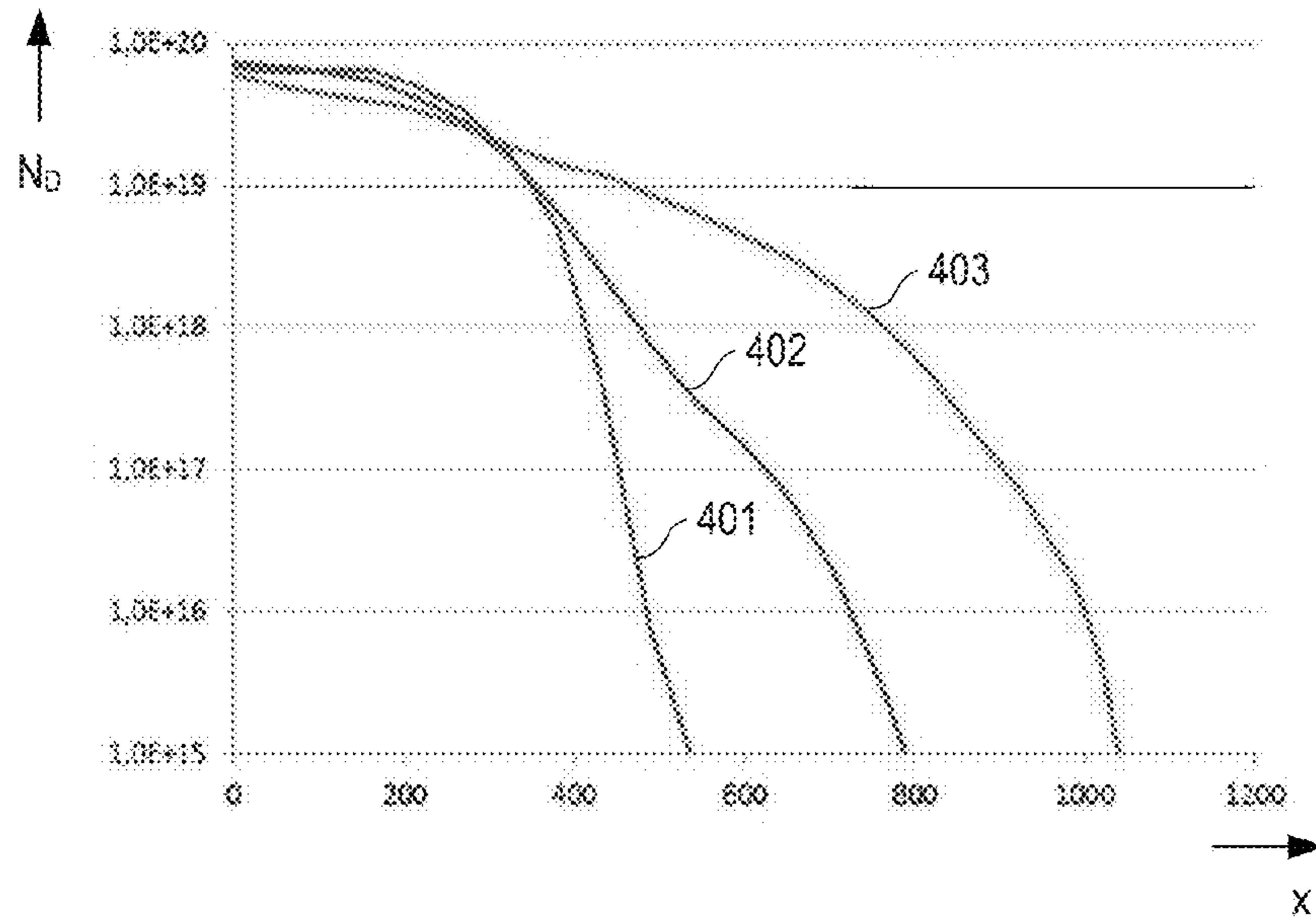

FIG 18

ADJUSTING THE CHARGE CARRIER LIFETIME IN A BIPOLAR SEMICONDUCTOR DEVICE

TECHNICAL FIELD

This disclosure in general relates to adjusting the charge carrier lifetime, and more particularly to adjusting the minority charge carrier lifetime in a bipolar power semiconductor device.

BACKGROUND

A bipolar power semiconductor device such as, for example, a power diode, a power IGBT, or a power thyristor, includes a first emitter region of a first conductivity type (doping type), a second emitter region of a second conductivity type, and a base region (often referred to as drift region) of the first conductivity type. Usually, the base region has a lower doping concentration than each of the first and second emitter regions.

A bipolar power semiconductor device can be operated in two different operation states, namely a conducting state (on-state), and a blocking state (off-state). In the conducting state, the first emitter region injects charge carriers of the first conductivity type into the base region, and the second emitter region injects charge carriers of the second conductivity type into the base region. These charge carriers injected into the base region by the first and second emitters form a charge carrier plasma in the base region.

When the bipolar power semiconductor device switches from the conducting state into the blocking state these charge carriers are removed from the base region. Losses that occur in the transition phase from the conducting state to the blocking state are dependent on how many charge carriers are present in the base region before the semiconductor device starts to switch from the conducting state to the blocking state, whereas the higher the amount of charge carriers the higher the losses. Basically, the number of charge carriers can be adjusted by adjusting the charge carrier lifetime, in particular the minority charge carrier lifetime, which is the average time it takes for a minority charge carrier to recombine. The shorter the minority charge carrier lifetime, that is the faster minority charge carriers recombine, the lower is the amount of charge carriers in the base region at the time of switching from the conducting state to the blocking state. However, conduction losses, which are losses that occur in the bipolar power semiconductor device in the conducting state, increase as the charge carrier lifetime decreases.

When the bipolar power semiconductor device switches from the conducting state to the blocking state a depletion region expands in the base region beginning at a pn junction between the base region and the second emitter region. Through this, charge carriers forming the charge carrier plasma are removed from the base region; this is known as reverse recovery. During reverse recovery there is a reverse recovery current flowing between the first and second emitter region. Such reverse recovery current is caused by the removal of charge carriers from the base region. This current finally drops to zero as the charge carriers have been removed or recombined. A slope of this reverse recovery current as it tends to zero defines the softness of the component. The steeper the slope, the less "soft" is the reverse recovery behaviour (switching behaviour) of the semiconductor device. However, a soft behaviour is desirable, because steep slopes may cause voltage overshoots in parasitic inductances connected to the semiconductor device and/or may cause oscillations or ringing in a circuit in which the semiconductor device is employed.

A soft reverse recovery behaviour can be obtained by having a "charge carrier reservoir" in those regions of the base region that are depleted towards the end of the switching process, wherein this charge carrier reservoir feeds the reverse recovery current towards the end of the switching process so as to soften a decrease of the reverse recovery current to zero. Such a "charge carrier reservoir" can be obtained by having a high charge carrier lifetime in those regions of the base region that are depleted towards the end of the reverse recovery process.

There is therefore a need to suitably adjust the charge carrier lifetime in a bipolar semiconductor device in order to have low switching losses and a soft switching behaviour.

SUMMARY

One embodiment relates to a method. The method includes implanting recombination center atoms via a first surface into a semiconductor body, and causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process.

Another embodiment relates to a semiconductor device. The semiconductor device includes a semiconductor body having a first surface and a second surface, recombination centers in a region between the first surface and the second surface, wherein a profile of the recombination centers in a vertical direction of the semiconductor body comprises a minimum spaced apart from each of the first and second surfaces and at least one maximum. A ratio between the at least one maximum and the minimum is less than 200.

BRIEF DESCRIPTION OF THE DRAWINGS

Examples are explained below with reference to the drawings. The drawings serve to illustrate certain principles, so that only aspects necessary for understanding these principles are illustrated. The drawings are not to scale. In the drawings the same reference characters denote like features.

FIGS. **1**A-**1**B illustrate one embodiment of a method for generating recombination centers in a semiconductor body in order to adjust the charge carrier lifetime;

FIG. **2** shows two embodiments of a distribution of recombination centers in the semiconductor body obtained based on different process parameters;

FIG. **3** illustrates the solubility limit of platinum (Pt) in silicon (Si) over the diffusion temperature;

FIG. **4** illustrates a modification of the method illustrated in FIGS. **1**A-**1**B;

FIGS. **5**A-**5**B illustrate one embodiment of reducing a recombination center concentration in the region of one surface of the semiconductor body;

FIG. **6** shows the recombination center distribution in the semiconductor body obtained based on the method explained with reference to FIG. **5**A-**5**B;

FIGS. **7**A-**7**B show one embodiment of a method for providing dopant atoms in the region of one surface of the semiconductor body;

FIGS. **8**A-**8**B show another embodiment of a method for providing dopant atoms in the region of one surface of the semiconductor body;

FIG. **9** shows one embodiment of a diode which is based on a semiconductor body shown in FIG. **4**B;

FIG. **10** shows forward voltages of six different diodes obtained by different processes;

FIG. **11** shows the temperature dependence of the forward voltage of one embodiment of a diode;

FIG. **12** shows the temperature dependence of the forward voltage of another embodiment of a diode;

FIG. **13** illustrates the implantation doses of recombination center atoms and corresponding diffusion temperatures that result in the same amount of recombination centers in a diode;

FIG. **14** illustrates a platinum concentration obtained in a semiconductor body by different process sequences;

FIG. **15** illustrates a modification of the method illustrated in FIGS. **1A-1B**;

FIG. **16** shows one embodiment of a diode implemented in a semiconductor body having an inner region and an edge region;

FIG. **17** shows a vertical cross sectional view of a semiconductor body in a laser annealing process; and

FIG. **18** shows the doping profile of three doped regions obtained by different methods.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying drawings. The drawings form a part of the description and by way of illustration show specific embodiments in which the invention may be practiced. It is to be understood that the features of the various embodiments described herein may be combined with each other, unless specifically noted otherwise.

FIGS. **1**A and **1**B schematically illustrate one embodiment of a method for producing recombination centers in a semiconductor body **100** in order to adjust the charge carrier lifetime. In particular, the method relates to adjusting the minority charge carrier lifetime in the semiconductor body **100**. The semiconductor body **100** includes a first surface **101** and a second surface **102** opposite the first surface **101**. FIGS. **1**A and **1**B show vertical cross sectional views of a section of the semiconductor body **100** during different method steps of the method.

The semiconductor body **100** may include a conventional semiconductor material such as, for example, silicon (Si), silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs), or the like. Although FIGS. **1**A and **1**B only show one section of one semiconductor body **100**, the process steps explained with reference to FIGS. **1**A and **1**B, as well as process steps explained with reference to other figures herein below, can be applied at once to a plurality of semiconductor bodies that are part of a semiconductor wafer. That is, these process steps can be applied to a semiconductor wafer which includes a plurality of semiconductor bodies, wherein the semiconductor wafer can be subdivided into the plurality of semiconductor bodies (dies) at the end of the manufacturing process. According to another embodiment, one wafer includes (is comprised of) only one semiconductor body.

The semiconductor body may include a basic doping such as, for example, an n-type basic doping. For example, a doping concentration of this a basic doping is between 1E12 cm^{-3} and 5E15 cm^{-3}, in particular between 1E13 cm^{-3} and 1E14 cm^{-3}. Dopant atoms that cause the basic doping are, e.g., phosphorous (P) atoms.

Referring to FIG. **1**A, the method includes implanting recombination center atoms via the first surface **101** into the semiconductor body **100**. Implanting the recombination center atoms may include implanting the recombination centers all over the first surface **101**. According to another embodiment explained with reference to FIG. **15** herein below implanting the recombination center atoms includes the use of an implantation mask that covers sections of the first surface **101** so as to prevent recombination center atoms from being implanted into these sections. According to one embodiment, implanting the recombination center includes directly implanting the recombination centers into the first surface **101**. According to another embodiment, the recombination center atoms are implanted through a scattering layer **200** (illustrated in dashed lines). The scattering layer can be formed on the first surface **101** (as shown) or can be distant from the first surface **101** (not shown). According to one embodiment, the scattering layer **200** includes an oxide such as, for example, silicon oxide (SiO_2). A thickness of the scattering layer **200** may be between 10 nanometers (nm) and 50 nanometers (nm).

According to one embodiment, the recombination center atoms include noble metal atoms, such as, for example, at least one of platinum (Pt) atoms, gold (Au) atoms and palladium (Pd) atoms. How deep the recombination center atoms are implanted into the semiconductor body **100** is dependent on an implantation energy. According to one embodiment the implantation energy is selected from between 10 keV and 200 keV, in particular between 120 keV and 180 keV. In FIG. **1**A, the dashed line labeled with reference character **110** illustrates the end of range of the implantation. That is, the dashed line illustrates how deep the recombination center atoms are implanted into the semiconductor body **100** from the first surface **101**. The distance between the end of range 110 and the first surface **101** is dependent on the implantation energy and increases as the implantation energy increases. According to one embodiment, the implantation dose is between 1E11 cm^{-2} and 1E14 cm^{-2} in particular between 5E11 cm^{-2} and 5E13 cm^{-2}.

Referring to FIG. **1**B, the method further includes a first diffusion process which causes the implanted recombination center atoms to diffuse in the semiconductor body **100**. In this diffusion process the recombination center atoms diffuse beyond the end of range in the direction of the second surface **102** but also in the direction of the first surface **101**. Further, in the diffusion process, the recombination center atoms are incorporated into the crystal lattice on substitutional sites by occupying vacancies of the (monocrystalline) semiconductor body **100** such that the recombination center atoms may act as recombination centers for charge carriers. This is explained in further detail below.

The distribution of the recombination center atoms after the first diffusion process is dependent on the process parameters such as the implantation dose, the diffusion temperature and the duration of the first diffusion process. According to one embodiment, the diffusion temperature is between 650° C. and 950° C., and the duration of the first diffusion process is between 1 hour and 2 hours. The diffusion temperature can be substantially constant during the first diffusion process. According to another embodiment, the diffusion temperature varies during the first diffusion process.

FIG. **2** shows two examples of the distribution of the recombination center atoms in the semiconductor body **100** after the first diffusion process. FIG. **2** shows the distribution of the recombination center atoms over the vertical direction x of the semiconductor body **100**. Referring to FIG. **2**, the distribution of recombination center atoms is basically U-shaped. That is, after the first diffusion process there is a first maximum of the recombination center atom concentration at the first surface **101** (which corresponds to the vertical position **0** in FIG. **2**), and a second maximum of the recombination center atoms at the second surface **102** (which corresponds to the vertical position d in FIG. **2**), and there is a minimum distant to the first and second surfaces **101**, **102**. The recombination center atom concentration in the first

maximum at the first surface **101** and the second maximum at the second surface **102** can be substantially the same.

FIG. **2** shows the distribution of active recombination center atoms in the semiconductor body **100**. "Active recombination center atoms" are those recombination center atoms that are incorporated in the crystal lattice of the semiconductor body **100** such that the recombination center atoms may act as recombination centers for charge carriers in the semiconductor body **100**. How many of the implanted recombination center atoms are activated is mainly dependent on the temperature in the diffusion process. This is explained with reference to two examples. In each of these examples platinum (Pt) atoms are implanted into a silicon (Si) semiconductor body with a thickness d of 500 micrometers (μm). The implantation dose D_{Pt} is 5E12 cm^{-2} in both examples. In the two examples, the diffusion parameters in the diffusion process are as follows.

Example 1

Temperature: 800° C.
Duration: 2 hours

Example 2

Temperature: 900° C.
Duration: 2 hours

That is, the two examples are only different in the diffusion temperature while the other parameters such as duration of the diffusion process and implantation dose are identical.

The distribution of the recombination center atoms (Pt atoms) obtained in the first example (Example 1) is represented by the distribution curve **201** shown in FIG. **2**, and the distribution of recombination center atoms obtained in the second example (Example 2) is represented by curve **302** shown in FIG. **2**. In the first example, the maximum concentration of activated recombination center atoms in the region of the first and second surfaces **101**, **102** is higher than in the second example. The maximum concentration N_{E1} in the first example is about 1E14 cm^{-3}, and the maximum concentration N_{E2} in the second example is about 5E14 cm^{-3}. These maximum concentrations N_{E1}, N_{E2} of the recombination center atoms at the first and the second surface **101**, **102** will be referred to as surface concentrations in the following.

FIG. **2** shows the distribution of the recombination center atoms on a logarithmic scale. As can be seen from FIG. **2**, the amount of activated recombination center atoms in the second example (see curve **302**) is significantly higher than in the first example (see curve **301**). At the lower diffusion temperature (800° C.) in the first example only about 13% of the implanted recombination center atoms are activated, while at the higher diffusion temperature (900° C.) in the second example substantially all (100%) of the implanted recombination center atoms are activated. Thus, the diffusion temperature significantly influences the distribution of the activated recombination center atoms in the method explained with reference to FIGS. **1**A and **1**B.

Referring to FIG. **2**, the diffusion temperature not only influences the amount of recombination center atoms that are activated, but also influences the profile of the distribution. At the higher temperature (see curve **302** in FIG. **2**) the U-shaped profile is shallower. That is, as a result of the higher diffusion temperature a ratio between the surface concentration and the minimum concentration is smaller than in the first example at the lower diffusion temperature. That is, $N_{E2}/N_{M2}<N_{E1}/N_{M1}$, where N_{M2} is the minimum recombination center concentration in the second example, and N_{M1} is the minimum recombination center concentration in the first example.

In the second example, the surface concentration is below the so-called solubility limit. The "solubility limit" is dependent on the temperature and defines the maximum amount of recombination center atoms that can be activated when employing a conventional process in which recombination center atom are diffused into the semiconductor body from a layer on the surface of the semiconductor body. As will be explained further below, the method explained with reference to FIGS. **1**A-**1**B makes it possible to achieve a concentration of recombination centers that is even higher than the solubility limit.

FIG. **3** schematically illustrates the solubility limit of platinum (Pt) in silicon (Si) over the temperature. Referring to FIG. **3** the solubility increases as the diffusion temperature increases. In case of platinum (as illustrated in FIG. **3**) the solubility increases from about 1.0 E13 at 700° C. to about 5.0E16 at 1.000° C. Referring to FIG. **3**, the solubility limit at 800° C. is about 1.0E14 cm^{-3}, and at 900° C. is about 2.0E15 cm^{-3}. Thus, in the second example explained before, the surface concentration is below the solubility limit.

In a conventional process for introducing recombination center atoms into a semiconductor body, a metal-semiconductor alloy such as, for example, a platinum silicide is formed on one surface of a semiconductor body, and metal atoms (platinum atoms) diffuse from the alloy into the semiconductor body. In this conventional process, the surface concentration corresponds to the solubility limit. This, however, may cause problems in view of obtaining a soft switching behavior of a semiconductor device that is based on a semiconductor body with those relatively high surface concentrations of recombination center atoms. This explained in further detail herein below. Thus, based on the method explained with reference to FIGS. **1**A-**1**B a lower surface concentration of recombination center atoms and a shallower U-profile of the recombination center atom distribution can be obtained.

Referring to FIG. **2**, the surface concentrations at the first and second surfaces **101**, **102** are substantially the same. That is, recombination center atoms that are implanted through the first surface **101**, in the first diffusion process, diffuse to the first surface **101** and the second surface **102**. Thus, the distribution of the recombination center atoms is widely independent of whether the recombination center atoms are implanted through the first surface **101** or the second surface **102**. Referring to one embodiment shown in FIG. **4** the recombination center atoms are implanted through the second surface **102** instead of the first surface **101**. The distribution of recombination center atoms obtained in this method substantially corresponds to the distributions shown in FIG. **2**.

According to another embodiment (not shown) recombination center atoms are implanted through both the first surface **101** and the second surface **102**. That is, a first part of the overall implantation dose is implanted through the first surface **101** and a second part is implanted through the second surface **102**.

As stated above, activated recombination center atoms (which will briefly be referred to as recombination centers in the following) promote the recombination of charge carriers and, therefore, influence the charge carrier lifetime. In particular, recombination centers influence the minority charge carrier lifetime in a semiconductor body. A distribution of recombination centers as shown in FIG. **2** may result in a lower charge carrier lifetime in regions close to the first and second surface **101**, **102**, and a higher charge carrier lifetime in regions in the middle between the first and second surfaces

101, 102. However, there are bipolar semiconductor devices where it is desirable to have a charge carrier lifetime in a region of one surface that is lower than the charge carrier lifetime obtained after the first diffusion process. That is, it may be desirable to have a charge carrier lifetime in the region of one surface that corresponds to the charge carrier lifetime in the middle of the semiconductor body, or is even below the charge carrier lifetime in the middle of the semiconductor body. This can be obtained by applying further method steps explained with reference to FIGS. 5A-5B.

For the purpose of explanation it is assumed that it is desired to increase the charge carrier lifetime in the region of the first surface 101. However, this is only an example. It is also possible to increase the charge carrier lifetime in the region of the second surface 102. In this case, the method steps applied to the first surface 101 and explained with reference to FIGS. 5A-5B need to be applied to the second surface 102.

Referring to FIG. 5A, the method includes forming a doped semiconductor region 11 in the semiconductor body 100 close to or adjoining the first surface 101. This doped semiconductor region 11 includes dopant atoms. According to one embodiment, the semiconductor body 100 has a basic doping of one doping type such as, for example, an n-doping before producing the doped region 11, and the doping type of the doped region 11 corresponds to the doping type of the basic doping. According to one embodiment, the doped region 11 is an n-type region and the dopant atoms are phosphorus (P) atoms. A maximum doping concentration of the doped region 11 is, for example, between 1E19 cm^{-3} and 1E21 cm^{-3}. Forming the doped region 11 includes introducing dopant atoms into those regions where the doped region 11 is to be formed, and activating the introduced dopant atoms. Introducing the dopant atoms may include at least one of an implantation and diffusion process. This is explained in further detail herein below. Activating the dopant atoms includes incorporating the dopant atoms into the crystal lattice of the semiconductor body. The dopant atoms incorporated into the crystal lattice cause stress in the crystal lattice.

Referring to FIG. 5B, the temperature in a second diffusion process and the stress in the crystal lattice cause self-interstitials to form in the doped region 11 and to diffuse from the doped region 11 deeper into the semiconductor body 100, that is, into those regions of the semiconductor body 100 that have the basic doping. The temperature in the second diffusion process is, for example, between 500° C. and the temperature of the first diffusion process. The duration of the second diffusion process is, for example, between 1 hour and 2 hours. The recombination center atoms can be introduced into the semiconductor body before or after the doped region 11 is produced, but, in either case, are introduced before the second diffusion process.

The self-interstitials diffusing deeper into the semiconductor body replace activated recombination center atoms (recombination centers) so that in those regions into which the self-interstitials diffuse the concentration of recombination centers is reduced by kick-out, that is, by moving recombination center atoms from substitutional sites to interstitial lattice sites where they are mobile, so that they can be gettered by the highly doped layer. This can be referred to as phosphorous diffusion gettering (PDG) when the dopant atoms are phosphorous atoms. The result of this gettering process is schematically illustrated in FIG. 6 which shows the concentration of recombination centers in the semiconductor body 100 after the process steps explained with reference to FIGS. 5A-5B.

Referring to FIG. 6, the concentration of recombination centers is substantially 0 in the doped region 11 (wherein d1 denotes the depth of the doped region 11 as seen from the first surface 101) and beyond the doped region 11 in those regions where the self-interstitials diffuse in the second diffusion process. In FIG. 6, d2 denotes the depth (as seen from the first surface 101) of the region in which the concentration of recombination centers is substantially zero, where d2>d1. According to one embodiment, d2 is less than 0.2d, wherein d is the thickness of the semiconductor body.

Further, adjacent the doped region 11, the concentration of recombination centers may substantially correspond to the minimum concentration in the middle of the semiconductor body. That is, the concentration of recombination centers in the region adjacent the doped region 11 is lower than in the same regions after the second diffusion process.

There are different ways to produce the doped region 11. Two embodiments are explained with reference to FIGS. 7A-7B and 8A-8B below. Referring to FIGS. 7A-7B, producing the doped region 11 may include implanting dopant atoms through the first surface 101 into the semiconductor body 100 (see FIG. 7A), and activating the implanted dopant atoms in an activation process so as to form the doped region 11 (see FIG. 7B). The activation process may include annealing the semiconductor body 100, at least in the region of the first surface 101. Annealing may include heating the semiconductor body to temperatures selected from a range of between 800° C. and 1100° C., in particular between 900° C. and 950° C. for a predefined activation time. According to one embodiment, the temperature is between 900° C. and 950° C. and the duration is between 30 minutes and 120 minutes.

Referring to FIGS. 8A-8B producing the doped semiconductor region 11 may include depositing a dopant atoms including layer from a gaseous dopant source on the first surface 101, and diffusing the dopant atoms from this layer via the first surface 101 into the semiconductor body 100. In FIG. 8A, a layer 220 including the deposited dopant atoms is schematically illustrated. According to one embodiment, the dopant atoms are phosphorous (P) atoms, the layer 220 is a phosphorous glass layer and the gaseous dopant source is one of PH_3 and $POCl_3$. For example, the temperature in the diffusion process is between 800° C. and 1100° C. In this method, a separate diffusion process is optional. The temperature in the deposition process is in the same range, i.e. 800° C. 1000° C., as the temperature in the diffusion process so that dopant atoms already diffuse into the semiconductor body 100 and are activated in the deposition process. That the method steps explained with reference to FIGS. 5A-5B are suitable to effectively reduce the concentration of recombination centers in those regions adjoining the doped region 11 can be verified experimentally by measuring the forward voltage of bipolar diodes that were produced based on different semiconductor bodies, namely based on semiconductor bodies which only underwent the implantation and first diffusion process explained with reference to FIGS. 1A-1B, and based on semiconductor bodies which additionally underwent the second diffusion process explained with reference to FIG. 5B.

FIG. 9 shows one embodiment a bipolar diode which is based on the semiconductor body shown in FIG. 5B and which has a distribution of recombination centers as illustrated in FIG. 6. Referring to FIG. 9, the diode includes a first emitter region adjacent a first surface 101. This first emitter region is formed by the doped region 11. The bipolar diode further includes a second emitter region 12 adjacent the second surface 102, and a base region 13 that separates the first emitter region 11 and the second emitter region 12. The

second emitter region **12** has a doping type complementary to the doping type of the first emitter region **11** and a higher doping concentration than the base region **13**. The doping concentration of the base region **13** may correspond the basic doping of the semiconductor body **100**. Optionally, the bipolar diode further includes a field-stop region **14** of the same doping type as the first emitter region **11** and more highly doped in the base region **13**. According to one embodiment, the field-stop region **14** adjoins the first emitter region **11**. Referring to another embodiment (not shown) the field-stop region **14** is distant to the first emitter region **11**.

Referring to FIG. **9**, the bipolar diode further includes a first load terminal **21** connected to the first emitter region **11**, and a second load terminal **22** connected to the second emitter region **12**. For the purpose of explanation it is assumed the first emitter region **11** is n-doped and the second emitter region **12** is p-doped. In this case, first load terminal **21** is a cathode terminal and the second load terminal **22** is an anode terminal of the bipolar diode. Further, it is assumed that the base region **13** has the same doping type as the first emitter region **11** so that a pn-junction **15** is formed between the second emitter region **12** and the base region **13**.

Depending on a voltage applied between the first and second load terminals **21**, **22** the bipolar diode is either conducting (in a conducting mode) or blocking (in a blocking mode). The bipolar diode is conducting when the voltage applied between the first and second load terminals **21**, **22** has a polarity that forward biases the pn-junction **15**, and the bipolar diode is blocking when the voltage applied between the first and second load terminals **21**, **22** has a polarity that reverse biases the pn-junction **15**.

When the bipolar diode is conducting the second emitter region **11** injects charge carriers of a first type into the base region **13** and the second emitter region **12** injects charge carriers of a second type complementary to the first type into the base region **13**. The charge carriers of the first type are electrons when the first emitter region **11** is n-doped, and the second charge carriers are holes when the second emitter region **12** is p-doped. The charge carriers injected by the first and second emitter regions **11**, **12** into the base region **13** form a charge carrier plasma in the base region **13**.

When the bipolar diode switches from the conducting mode to the blocking mode, a space charge region (depletion region) expands beginning at the pn-junction **15** in the base region **13**. This depletion region expanding in the base region **13** causes the charge carrier plasma to be removed from the base region **13**, wherein a current flows through the bipolar diode until the charge carrier plasma is completely removed from the base region **13**.

The amount of charge carriers in the charge carrier plasma when the bipolar diode is conducting can be adjusted by adjusting the minority charge carrier lifetime in the base region **13**. A stated above, the minority charge carrier lifetime can be adjusted by providing recombination centers in the base region **13**. Basically, the higher the concentration of recombination centers, the lower the minority charge carrier lifetime, and the smaller the amount of charge carriers in the charge carrier plasma. Thus, the smaller the amount of charge carriers in the charge carrier plasma, the lower are reverse recovery losses, which are the losses that occur when the bipolar diode switches from the conducting mode to the blocking mode. The higher the amount of charge carriers in the charge carrier plasma, the longer it takes for the charge carrier plasma to be removed from the base region **13** and the longer a current flows through the bipolar diode when the bipolar diode switches from the conducting mode to the blocking mode.

At the end of the reverse recovery process, that is, at the end of the process in which the charge carrier plasma is removed from the base region **13** the current through the bipolar diode turns to zero. Since abrupt changes of the current through the bipolar diode may cause voltage peaks in inductances in a circuit (not shown) connected to the bipolar diode it may be desirable for the current at the end of the reverse recovery process to "softly" turn to zero. This can be obtained by suitably adjusting the minority charge carrier lifetime in those regions of the base region **12** that are depleted towards the end of the reverse recovery process. In the bipolar diode shown in FIG. **9**, these are the regions distant to the pn-junction **15** and close to the first emitter region **11** and the field-stop region **14**, respectively. In particular, the charge carrier lifetime is adjusted such that the charge carrier lifetime in those regions of the base region **13** which are depleted towards the end of the reverse recovery process corresponds to the minority charge carrier lifetime or is even higher than the minority charge carrier lifetime in those regions closer to the pn-junction **15** and depleted at the beginning of the reverse recovery process.

Referring to FIG. **6**, the method explained with reference to FIGS. **1A-1B** and **5A-5B** results in a semiconductor body that meets these requirements concerning the charge carrier lifetime. This has been verified by producing six samples of bipolar diodes that are based on differently processed semiconductor bodies. The following features of the bipolar diode were identical in each of the samples:

Basic n-doping of the semiconductor body (doping concentration of the base region 13)	1E13 (specific resistance: 450 Ω cm)
Thickness d of the semiconductor body 100	520 μm
p-dopant dose of the second emitter region 12	3E13 cm^{-2}
Depth d2 of the second emitter region 12 (distance between the second surface 102 and the pn-junction 15)	6 μm
n-dopant dose of the first emitter region 11	5E15 cm^{-2}
Depth d1 of the first emitter region 11	0.8 μm
Maximum doping concentration of the first emitter region 11	2E20 cm^{-3}
Maximum doping concentration of the field-stop region 14	1E15 cm^{-3}
Depth of the field-stop region 14 from the first surface 101	30 μm

The individual samples were different in view of producing the recombination centers (adjusting the minority charge carrier lifetime). In four (samples 1-4) of the six samples, platinum atoms were implanted and diffused as explained with reference to FIGS. **1A-1B**, while in two (samples 5-6) of the six samples platinum atoms were diffused from a platinum silicide in a conventional way. Further, in three of the six samples (samples 2, 4, 6) a second diffusion process was performed as explained with reference to FIGS. **5A-5B**, while in the other three samples (samples 1, 3, 5) the second diffusion process was omitted. In case of sample 6, the platinum silicide was removed before the second diffusion process.

The details of producing the recombination centers in the individual semiconductor bodies are summarized below.

Sample 1	
Way of introducing platinum atoms	implantation
Implantation dose	1E12 cm^{-2}
Temperature of the first diffusion process	825° C.

-continued

Sample 1	
Way of introducing platinum atoms	implantation
Temperature of the second diffusion process	— (no second diffusion process)

Sample 2	
Way of introducing platinum atoms	implantation
Implantation dose	1E12 cm^{-2}
Temperature of the first diffusion process	825° C.
Temperature of the second diffusion process	600° C.

Sample 3	
Way of introducing platinum atoms	implantation
Implantation dose	2E12 cm^{-2}
Temperature of the first diffusion process	825° C.
Temperature of the second diffusion process	— (no second diffusion process)

Sample 4	
Way of introducing platinum atoms	implantation
Implantation dose	1E12 cm^{-2}
Temperature of the first diffusion process	825° C.
Temperature of the second diffusion process	600° C.

Sample 5	
Way of introducing platinum atoms	diffusion from a platinum silicide formed on one of the surfaces of the semiconductor body
Implantation dose	—
Temperature of the first diffusion process	795° C.
Temperature of the second diffusion process	— (no second diffusion process)

Sample 6:	
Way of introducing platinum atoms	diffusion from a platinum silicide formed on one of the surfaces of the semiconductor body
Implantation dose	—
Temperature of the first diffusion process	795° C.
Temperature of the second diffusion process	600° C.

Recombination centers formed in the semiconductor body, in particular in the base region **13**, not only reduce the minority charge carrier lifetime, but also increase the forward voltage V_F of the bipolar diode. The "forward voltage" is the

voltage between the first and second load terminals **21**, **22** at a rated current flowing through the bipolar diode when the bipolar diode is in the conducting mode.

In the diodes according to samples 1-6 explained above the forward voltage was measured at a rated current of 100 A. The forward voltages obtained in these measurements are illustrated in FIG. **10**. Referring to the results obtained for samples 1 and 3, which are only different in the implantation dose of the platinum atoms, a higher implantation dose and, therefore, a higher concentration of recombination centers results in a higher forward voltage (the forward voltage of sample 3 is higher than the forward voltage of sample 1). The same can be seen from samples 2 and 4 which are only different in the implantation dose (the forward voltage of sample 4 is higher than the forward voltage of sample 2). Further, the forward voltage of sample 2 is lower than the forward voltage of sample 1, wherein samples 1 and 2 are only different in that a second diffusion process as explained with reference to FIGS. **5**A-**5**B was performed in sample 2. This strongly indicates that the second diffusion process results in a reduction of recombination centers in the base region **13** in those regions in which self-interstitials diffuse from the doped region **11**. The same result can be seen by comparing samples 3 and 4 which are only different in that a second diffusion process was performed in sample 4; the forward voltage V_F obtained for sample 4 is lower than the forward voltage V_F obtained for sample 3.

In the conventional process, that is the process of samples 5-6, no significant differences between the forward voltages was monitored. This strongly indicates that in the conventional process the concentration of recombination centers close to the surfaces of the semiconductor body is so high that no significant reduction of the recombination centers can be obtained by the second diffusion process.

Thus, if the surface concentration of the recombination centers is below the solubility limit, then the concentration of recombination centers can be effectively reduced by diffusing self-interstitials from the doped region **11** deeper into the semiconductor body. Recombination center concentrations below the solubility limit can be obtained by implanting recombination center atoms into the semiconductor body instead of diffusing the recombination center atoms from an alloy. In particular, implanting the recombination center atoms may include implanting the recombination center atoms with an implantation dose such that all (100%) of the implanted recombination center atoms are activated at a given temperature. This temperature is, for example, between 700° C. and 1000° C., in particular between 750° and 950° C.

Further, by suitably adjusting the process parameter in the process of implanting the recombination center atoms and diffusing the implanted recombination center atoms the temperature coefficient of the forward voltage can be adjusted. This is explained with reference to FIGS. **11**-**13** below.

FIG. **11** shows the forward voltage V_F and the corresponding forward current I_F of an example bipolar diode at a first temperature T**1** such as, for example, 25° C. and a second temperature T**2** such as, for example, 125° C. As can be seen from FIG. **11**, the forward voltage V_F increases as the forward current I_F increases. The forward current I_F is, for example, a current driven through the bipolar diode by a load (not shown in the figures) connected in series with the bipolar diode. The relationship between the forward voltage V_F and the forward current I_F is dependent on the temperature. That is, at different temperatures the forward voltage V_F increases differently as the forward current increases. Generally, it is desirable for the forward voltage V_F to have a positive temperature coefficient. A "positive temperature coefficient" means that at a given

forward current I_F which is equal to or higher than the rated current the forward voltage V_F is the higher, the higher the temperature is. A "positive temperature coefficient" also means that at a given forward voltage V_F the forward current I_F is the lower, the higher the temperature is.

For example, a positive temperature coefficient of a bipolar diode is beneficial in a circuit application in which several bipolar diodes are connected in parallel. If each of the bipolar diode has a positive temperature coefficient and if the temperature of one of these bipolar diodes becomes higher than the temperatures of the other bipolar diodes, then the current through the bipolar diode with the higher temperature decreases. This has the effect that the power dissipated in the bipolar diode with the higher temperature decreases, so as to counteract a further increase of the temperature of this bipolar diode. In case of a negative temperature coefficient of the bipolar diodes, a higher temperature of one bipolar diode would result in an increasing current through this bipolar diode which, in turn, would result in an increase of power dissipated in the bipolar diode with the higher temperature, which would further increase the temperature of this bipolar diode and may finally cause the bipolar diode to be damaged or destroyed.

In the example shown in FIG. **11**, the forward voltage V_F has a positive temperature coefficient at operation points above a temperature stable operation point. Each operation point is defined by the forward voltage V_F and the corresponding forward current I_F at one temperature. The temperature stable operation point is defined by forward voltage V_{F0} and a corresponding forward current I_{F0}, wherein the forward voltage V_F is independent of the temperature in this operation point. At operation points below this temperature stable operation point V_{F0}, I_{F0}, the temperature coefficient is slightly negative.

FIG. **12** illustrates an example in which the forward voltage V_F has a negative temperature coefficient. In this example, for each forward voltage V_F the forward current I_F increases as the temperature increases.

Experiments have shown that the temperature behavior of the forward voltage V_F is dependent on the concentration of recombination centers in the base region **13** close to the pn junction **15**. This is explained below.

In the conventional process explained before, the concentration of recombination centers can only be varied by varying the temperature at which the recombination centers diffuse from the alloy into the semiconductor body. In this conventional process, the surface concentration always corresponds to the solubility limit. In a power diode, such as a power diode explained with reference to the FIG. **9**, the pn junction **15** is usually close to the surface. That is, a distance of the pn junction **15** to the nearest surface is usually less than 2% of the thickness of the semiconductor body **100**. For example, in a (silicon) power diode with a voltage blocking capability of 4.5 keV the thickness d of the semiconductor body is about 500 micrometers while the distance of the pn junction to the second surface **102** is only about 6 micrometers, which is 1.2% of the thickness of the semiconductor body. Thus, the concentration of recombination centers in the region of the pn junction can be considered to substantially correspond to the surface concentration.

As stated above, the overall amount of recombination centers in the base region **13** affects the forward voltage, wherein the forward voltage V_F increases as the overall amount of recombination centers increases. In the conventional process, the amount of charge carriers and, therefore, the forward voltage at a rated current can only be adjusted by the temperature. However, experiments have shown that producing the recombination centers in the conventional process results in a slightly negative temperature coefficient of the forward voltage.

While in the conventional method there is only one parameter that can be varied in order to adjust the overall amount of recombination centers in the base region, the method explained with reference to FIGS. **1A-1B** includes two parameters that can be varied, namely the implantation dose of the recombination center atoms and the temperature in the first diffusion process. This is explained with reference to FIG. **13** below.

FIG. **13** shows a curve that illustrates the implantation dose of recombination center atoms and the corresponding temperature in the first diffusion process in order to obtain a predefined amount of recombination centers in the base region **13** of a bipolar diode. This predefined amount of recombination centers corresponds to a predefined forward voltage at a rated current. The curve shown in FIG. **13** was based on a bipolar diode with the following parameters:

Basic n-doping of the semiconductor body (doping concentration of the base region 13)	1E13 (specific resistance: 450 Ω cm)
Thickness d of the semiconductor body 100	520 μm
p-dopant dose of the second emitter region 12	3E13 cm^{-2}
Depth d2 of the second emitter region 12 (distance between the second surface 102 and the pn-junction 15	6 μm
n-dopant dose of the first emitter region 11	5E15 cm^{-2}
Depth d1 of the first emitter region 11	0.8 μm
Dopant dose of the field-stop region 14	8E11 cm^{-2}
Depth of the field-stop region 14 from the first surface 101	60 μm

At a rated current of, for example, 100 A this bipolar diode has a forward voltage V_F of about 1.8V when no recombination centers are produced. Producing recombination centers increases the forward voltage V_F. In the experiment underlying the curve shown in FIG. **13** recombination centers were produced in the base region to such an extent that the forward voltage V_F at the rated current was about 2.8V. In the example, the semiconductor body **100** includes silicon (Si) and the recombination center atoms are platinum (Pt) atoms.

In the following, the implanted dose of recombination centers and the corresponding temperature of the first diffusion process that result in a particular amount of recombination centers (a particular forward voltage V_F) will be referred to as parameter pair. In FIG. **13**, parameter pairs that result in the same forward voltage (about 2.8 V in this example) are represented by the curve shown in the figure. Referring to FIG. **13**, there is a plurality of parameter pairs that result in the same amount of recombination centers in the base region. The diffusion temperature increases as the implantation dose decreases. That is, at lower implantation doses higher temperatures are required to activate the desired amount of recombination center atoms. In other words, at higher implantation doses the corresponding temperature is smaller so that at higher implantation doses a smaller portion of the implanted recombination center atoms is activated in the base region than at lower implantation doses. In the experiment, the implantation dose was varied between 1E12 cm^{-2} and 1E13 cm^{-2} resulting in a variation of the temperature between about 750° C. and about 815° C. The dashed line in FIG. **13** represents the temperature (about 795° C.) that is required in the conventional process to diffuse in and activate recombination center atoms to such an extent that the forward voltage V_F is about 2.8V.

Measurements have shown that the forward voltage V_F of the diode produced in accordance with the standard process has a negative temperature coefficient (TC). The same applies to diodes produced with first diffusion temperatures higher than the temperature of the conventional process and relatively low implantation dose. However, at lower temperatures such as, for example, temperatures below 850° C., in particular below 790° C. and higher implantation doses such as, for example, higher than 3E12 cm^{-2} a positive temperature coefficient (TC) of the forward voltage was detected. One possible reason for this is explained below.

The implantation of recombination center atoms into the semiconductor body **100** causes implantation damages, so-called point defects. Those defects mainly occur in the region of that surface into which the recombination center atoms are implanted and the concentration of those defects increases as the implantation dose increases. Referring to the explanation above, the recombination center atoms can be implanted into the semiconductor body **100** via the first surface **101** or the second surface **102**. However, in the first diffusion process, these defects rapidly diffuse in the semiconductor body **100** so that point defects can be found in the region of the implantation surface (which is the surface into which the ions are implanted) as well as in the region of the opposite surface. Thus, referring to the embodiments explained with reference to FIGS. **4** and **9**, point defects in the second emitter region **12** can also be generated by implanting the recombination center atoms into the first surface **101** opposite the second surface **102**.

These point defects enable platinum to be substitutionally incorporated into the crystal lattice of the semiconductor body **100**. In particular, these point defects may result in a concentration of incorporated (activated) platinum atoms in the region of the first and second surface **101**, **102** which is above the solubility limit at the temperature of the first diffusion process, such as above the solubility limit at a temperature of 790° C. or higher. "In the region of the first and second surfaces **101**, **102**" means in a region close to these first and second surfaces **102**. That is, for example, in a region having a width of between 500 nanometers and 1 micrometer beginning at the respective surface **101**, **102**. For example, in a bipolar diode as shown in FIG. **9**, the high platinum concentration in the region of the second surface, that is, in the region of the second emitter **12** reduces the efficiency of the second emitter **12**, such that at a given (rated) current a voltage drop across the second emitter **12** increases as the operation temperature increase. This results in a positive temperature coefficient, while the increased voltage drop across the second emitter **12** does not significantly increase the forward voltage which is mainly defined by the base region **13** and the concentration of recombination center atoms therein.

The above explanation with regard to FIG. **13** may be summarized as follows. Referring to FIG. **13**, the forward voltage V_F substantially is the same, that is, the doping concentration of the base region (**13** in FIG. **9**) substantially is the same when the implantation dose increases but the temperature of the first diffusion process decreases. However, the higher implantation dose in connection with the higher concentration of implantation defects (which supposedly agglomerate in the region of the surfaces **101**, **102**) may result in concentrations of recombination centers in the region of the surfaces **101**, **102** which are above the solubility limit at the temperature of the diffusion process. These high concentrations, in turn, reduce the efficiency of the emitter (the second emitter **12** in FIG. **9**) which has a doping type complementary to the doping type of the base region **13** and, therefore, result in a positive temperature coefficient.

It has been verified by experiments, that implanting recombination center atoms followed by a first temperature (diffusion) process may result in a concentration of recombination center atoms which is higher than the solubility limit at the temperature of the first temperature process. The result of one of these experiments is shown in FIG. **14**. In this experiment, platinum atoms were diffused into a semiconductor body in accordance with a conventional diffusion process at a diffusion temperature of 790° C. The surface concentration obtained through this is illustrated in dashed lines in FIG. **14** (see the graph labeled "Standard 790° C." in FIG. **14**). Further, in this experiment, platinum atoms were introduced in a comparable semiconductor body by implanting the platinum atoms and diffusing the implanted atoms at the same temperature as the conventional process, that is, at 790° C. The implantation dose was selected such that in an inner region of the semiconductor body, that is, a region corresponding to the base region in the embodiments explained herein before the concentration of recombination center atoms was substantially the same in both processes. Referring to FIG. **14** a significantly higher platinum concentration can be obtained by implanting and diffusing instead of diffusing, only. While the platinum concentration at the surface is about 2E14 cm^{-3} (which corresponds to the solubility limit at 790° C.) in the conventional process it is about 3E15 cm^{-3} in the implantation and diffusion process.

The implantation process explained with reference to FIG. **1**A can be performed such that the recombination center atoms are implanted into the semiconductor body **100** all over the first surface **101**. In this case, after the first diffusion process, there may be a vertical variation of the recombination center concentration as shown in FIG. **2**. That is, the concentration of recombination centers may vary in the vertical direction of the semiconductor body **100** which is a direction perpendicular to the first surface. However, in a lateral direction, which is a direction parallel to the first surface **101** there is substantially no variation of the recombination center concentration.

According to one embodiment shown in FIG. **15** the recombination center atoms are implanted into the first surface **101** of the semiconductor body **100** using an implantation mask **300**. The implantation mask covers sections of the first surface **101** and prevents recombination center atoms from being implanted in those regions of the first surface **101** covered by the implantation mask **300**. In this process, a lateral variation of the recombination center concentration can be obtained. In particular, there can be regions of the semiconductor body **100** below the implantation mask **300** where, after the first diffusion process, the concentration of recombination centers is substantially zero. In the first diffusion process, the implanted recombination center atoms not only diffuse in the vertical direction of the semiconductor body **100** but also in the lateral direction. However, the maximum diffusion length in the lateral direction substantially can be adjusted by the thermal budget involved in the diffusion process, that is, by the temperature and the duration in the first diffusion process. According to one embodiment, the thermal budget is selected such that the diffusion width in the lateral direction substantially corresponds to the thickness d of the semiconductor body. Thus, dependent on the size of the implantation mask **300** there can be regions in the semiconductor body **100** where no recombination centers are produced. According to one embodiment, the temperature process is an RTA (Rapid Thermal Annealing) process.

In FIG. **15**, the dotted line schematically illustrates the situation after the first diffusion process. The dotted line represents a border between those regions **121** of the semi-

conductor body **100** in which recombination center atoms diffuse from the end of range in the first diffusion process and those regions **122** in which recombination center atoms neither are implanted nor diffuse.

Such lateral variation of the recombination center atoms may be used in a variety of different semiconductor device. For example, the method can be used to adjust recombination centers substantially only in an edge region of a semiconductor device. This is explained with reference to FIG. **16**.

FIG. **16** illustrates a vertical cross sectional view of a bipolar diode integrated in a semiconductor body **100**. The semiconductor body includes an inner region **131** in which the first and second emitter regions **11**, **12** and the base region **13** are arranged, and an edge region **132** that surrounds the inner region **131**. The edge region **132** may adjoin an edge surface of the semiconductor body (as illustrated in FIG. **16**). However according to another embodiment, the edge region **132** separates the inner region **131** with the active device regions (emitter regions **11**, **129**) from other devices integrated in the same semiconductor body. According to one embodiment, the method explained with reference to FIG. **14** is used to generate recombination centers in the edge region **132**. In this embodiment, recombination center atoms are implanted via the first surface **101** or the second surface **102** into the semiconductor body **100** with an implantation mask **300** covering the inner region **131** and leaving uncovered the edge region. Such implantation mask is schematically illustrated on the second surface **102** in FIG. **16**. In the implantation process a scattering layer (not shown in FIG. **15**) can be used. After the implantation process, the implanted recombination center atoms diffuse in the semiconductor body **100** substantially in the edge region **132** so as to produce recombination centers in the edge region. The process parameters such as implantation dose, implantation energy, and diffusion temperature may correspond to the parameters explained before.

It should be noted that the methods explained with reference to FIGS. **1A-1B** and **15** can be combined. That is, the method explained with reference to FIG. **1A-1B** may be used to generate recombination centers all over the semiconductor body **100** while additionally the method explained with reference to FIG. **14** may be used to additionally produce recombination centers in selected regions of the semiconductor body **100**.

The method explained with reference to FIG. **15** is not restricted to be used for producing recombination centers in an edge region of a semiconductor device, but may be used in each case where it is desired to selectively produce recombination centers in certain regions of a semiconductor body while omitting other regions of the semiconductor body. For example, an IGBT and a diode are integrated in one semiconductor body and recombination centers are only produced in those regions that include the diode.

Referring to the above, forming the doped region **11** may include an implantation and/or a diffusion process at temperatures higher than 950° C. and durations of between 30 minutes and 100 minutes. If those temperatures, which are above the temperature range of the first diffusion process, would be applied to the semiconductor body **100** for a relatively long time, such as more than several minutes, after the recombination center atoms had been implanted and diffused in the first diffusion process substantially all recombination center atoms would be removed by the gettering effects explained above. That is, at those high temperatures self-interstitials would diffuse deep into the semiconductor body **100** and replace the recombination center atoms at substitutional sites of the crystal lattice. These self-interstitials result from introducing the dopant atoms that finally form the doped region **11**. In order to prevent this, the doped region **11** may be formed before implanting the recombination center atoms and before the first diffusion process. The optional second diffusion process, which may include temperatures of between 500° C. and the maximum temperature in the first diffusion process and which may be used to reduce the recombination center concentration close to the doped region **11**, may then be performed after forming the doped region and after the first diffusion process.

According to another embodiment, the doped region **11** is formed after implanting the recombination center atoms and the first diffusion process, but before the optional second diffusion process. The process of forming the doped region **11** before implanting the recombination center atoms and the first diffusion process may include implanting the dopant atoms into the first surface **101**, as explained with reference to FIG. **7A**, and one of a laser annealing and an RTA (Rapid Thermal Annealing) process to activate the implanted dopant atoms.

The laser annealing process includes heating by laser pulses the semiconductor body in the region of the first surface **101** such that the semiconductor material in this region melts and afterwards recrystallizes, whereas during recrystallization the introduced dopant atoms are incorporated into the crystal lattice and thereby activated. The doping concentration of the doped region **11** obtained by this method is substantially homogenous, whereas the doping level is dependent on the dopant dose introduced in the implantation process and the depth of the doped region **11**. The "depth" of the doped region is the dimension the doped region **11** extends into the semiconductor body **100** from the first surface **101**. For example, a dopant dose is selected from a range of between 1E15 cm^{-2} and 1E16 cm^{-2}. The depth of the doped region **11** is, for example, in a range of between 400 nanometers and 1000 nanometers (=1 micrometer). If, for example, the dopant dose is 4E15 cm^{-2} and the depth of the emitter is 400 nanometers, a doping concentration of the doped region **11** of 1 E22 cm^{-3} (=4E15 cm^{-2}/4E-7 cm) may result if 100% of the introduced dopant atoms are activated. However, dependent on the specific type of the laser annealing process only between 30% and 80% of the introduced dopant atoms may become electrically active.

The depth of the doped region **11** can be adjusted by suitably selecting a wavelength of the laser light and the laser energy in the laser annealing process. In order for the laser energy to be absorbed in a region close to the first surface **101** laser light with a relatively short wavelength may be used. According to one embodiment, the semiconductor body **100** comprises silicon, and the wavelength of the laser light is selected from a range of between 300 nanometers and 350 nanometers. The laser energy is, for example, selected from a range of between 3 J/cm^2 and 4 J/cm^2. The relatively short wavelength of the laser light mentioned before causes the laser energy to be absorbed substantially within a region that extents between 20 nanometers and 30 nanometers from the first surface **101** into the semiconductor body. The region where the semiconductor body **100** melts and recrystallizes extends deeper than those 20-30 nanometers and may extend between 300 nanometers and 500 nanometers. The laser light is applied to the first surface **101** in laser pulses, whereas a duration of those laser pulses may be selected such that in the semiconductor body melts for less than several 100 nanoseconds (ns) and then recrystallizes. According to one embodiment, the semiconductor body, in the region of the first surface **101**, is melted for the less than 300 nanoseconds and then recrystallizes. For example, the duration of one laser pulse is

about 150 ns. The laser annealing process may include applying a plurality of laser pulses to the first surface **101**, wherein each of these laser pulses is directed to another section of the first surface **101** until a desired area of the first surface **101** has been melted and recrystallized. The individual sections may slightly overlap. Operating the laser in this way is referred to as stitched mode. This desired area may include the complete surface **101** or, alternatively, may include only a section of the first surface **101**.

In the laser annealing process, surface region of the semiconductor body **100** are heated for such a short time period that substantially no diffusion or gettering of the recombination centers introduced before may occur in this time period. "Surface regions" of the semiconductor body **100** are regions adjacent the first surface **101** of the semiconductor body **100**.

According to one embodiment, the laser annealing process includes forming an anti-reflective coating (ARC) layer **300** on the first surface **101** and directing the laser light in the laser annealing process to this ARC layer **300**. This is schematically illustrated in FIG. **17**.

FIG. **17** shows a vertical cross sectional view of the semiconductor body **100** after introducing the dopant atoms and before the laser annealing process. Reference character **11'** denotes those regions of the semiconductor body **100** adjacent the first surface into which dopant atoms where introduced and which is melted by the laser annealing process so as to form the doped region **11**. The ARC layer **300** helps to increase the efficiency of the laser annealing process by avoiding or at least reducing reflections of the laser light at the first surface **101**. This reduces losses by reflection and increases the amount of laser energy dissipated in the surface region.

According to one embodiment, the ARC layer **300** includes one of a silicon oxide (SiO_2) layer and a silicon nitride (Si_3N_4) layer. The use of an ARC layer **300** may cause the melted zone (the zone where the semiconductor body is melted) to extend deeper from the first surface **101** than in a method where no ARC layer **300** is used. This is explained with reference to FIG. **18** below.

FIG. **18** shows the doping concentration in a doped region **11** obtained by three different methods. In FIG. **18**, curve **401** represents a doping profile obtained by a laser annealing process without ARC layer **300**, curve **402** represents the doping profile obtained by a laser annealing process using a silicon oxide ARC layer **300** and, for comparison, curve **403** represents the doping profile obtained by an implantation and diffusion process as explained with reference to FIGS. **7**A-7B. The curves **401**-**403** shown in FIG. **18** are based on three different experiments, wherein the implantation dose was the same in each of these three experiments. Referring of the above, the implantation dose may be selected from a range of between 1E15 cm^{-2} and 1E16 cm^{-2}. In the experiments underlying the doping profiles shown in FIG. **18** the dopant dose was about 5E15 cm^{-2}. By integrating the doping concentration according to the different doping profiles **401**-**403** it can be shown that the overall number of activated dopant atoms is substantially the same in each of the three cases. In this specific embodiment, the integral of the doping concentration is about 2E15 cm^{-2} in each case, so that in this case about 40% of the implanted dopant atoms have been activated.

As can be seen from FIG. **18**, the doped region **11** obtained by the laser annealing process with ARC layer (curve **402**) extends deeper into the semiconductor body **100** than the doped region **11** obtained by the laser annealing process without ARC layer (curve **401**). The laser annealing processes (curves **401**, **402**) result in sharper doping profiles than the implantation and diffusion process (curve **403**). Furthermore, the doped region **11** formed by a laser annealing process extends less deep into the semiconductor body **100** than the doped region **11** obtained by the implantation and diffusion process. The surface concentration, which is the doping concentration of the doped region **11** at the first surface **101** is substantially the same in each of the three methods.

An RTA process, as an alternative to a laser annealing process, may include heating the first surface **101** to a temperature selected from a range of between 800° C. and 1050° C., in particular between 900° C. and 950° C. for an activation time of between 5 seconds and 5 minutes. In particular, the activation time is selected from between 10 seconds and 3 minutes. Heating the first surface **101** may include heating the first surface **101** by one of a lamp and a laser. By virtue of the relatively short activation period, a diffusion or gettering of the recombination centers can be widely prevented.

According to one embodiment, the method, after forming the recombination centers in the semiconductor body **100**, includes reducing the thickness of the semiconductor body **100** by removing a layer of semiconductor material at at least one of the first and the second surface **101**, **102**. Removing the semiconductor material may include at least one of an etching process, a mechanical polishing process, or a chemical-mechanical polishing process (CMP). Referring to FIG. **2**, forming the recombination centers in accordance with one of the methods explained before results in a maximum of the recombination center concentration close to the first and the second surface **101**, **102**. That is, the recombination center concentration increases towards the first and the second surface **101**, **102**. By removing semiconductor material at the first and/or surface **101**, **102** those sections of the semiconductor body **100** are removed where the maximum of the recombination center concentration is. Through this, a more homogenous distribution of recombination centers in the semiconductor body **100** can be obtained. According to one embodiment the thickness of the removed semiconductor material is selected from a range of between 200 nanometers and 2 micrometers, in particular between 500 nanometers and 1 micrometer. Such material layer may be removed at only one of the first and second surfaces **101**, **102** or at both surfaces **101**, **102**.

Forming the doped region **11** after forming the recombination centers in the semiconductor body **100** can be beneficial in several ways. First, it allows to remove semiconductor material at at least one of the first and second surfaces **101**, **102** to obtain a more homogenous distribution of the recombination centers. Second, catalytic effects of the doped region **11** on the generation of recombination centers can be prevented. Experiments have given cause to the assumption that the presence of the doped region **11** at the time of introducing and activating the recombination center atoms causes a segregation and pile up of recombination center atoms at the first surface **101**. This may negatively influence the forward voltage of the device. Third, the recombination center atoms may form pair complexes with the dopant atoms from the doped region **11**. For example, if the recombination center atoms are platinum atoms and the dopant atoms in the doped region **11** are phosphorous atoms so-called phosphorous-platinum pairs may be formed. The presence of those pair complexes may affect, in particular decrease, the forward voltage. As segregation and the formation of pair complexes is difficult, if not impossible to predict segregation and/or pair complexes may result in unpredictable variations of the forward voltage. That is, a group of devices formed by the same process may exhibit a large standard deviation of the forward voltage.

Referring to FIG. **9**, the semiconductor device may include a field-stop region **14**. The field-stop region **14** may adjoin the

doped region **11** (as shown) or may be spaced apart from the doped region **11**. Forming the field-stop region may include implanting protons (hydrogen ions) via the first surface **101** and an annealing process at temperatures of between 220° C. and 500° C. and a duration of between 30 minutes and 10 hours. In the annealing process n-doping complexes form in those regions into which the protons had been implanted. Those n-doping complexes are referred to as hydrogen induced donors. As the temperature in this annealing process is lower than the temperatures in the first diffusion process and the second diffusion process, the field-stop region may be formed after these diffusion processes. According to one embodiment, the field-stop region **14** is formed to have a maximum doping concentration of 1E15 cm^{-3}.

Although the semiconductor device shown in FIG. **9** is a diode the method explained herein above is not restricted to be used in processes for manufacturing diodes. Moreover, the device structure with the base region **13**, the doped region **11**, the optional field-stop region **14** and the recombination centers at least in the base region may be used in any type of bipolar devices. Examples of those further bipolar devices include, but are not restricted to, IGBTs (Insulated Gate Bipolar Transistors), in particular RC (Reverse Conducting) IGBTs, and GTO (Gate Turn Off) thyristors.

By the method explained herein before a relatively homogenous concentration of the recombination center atoms in the vertical direction x of the semiconductor body **100** can be obtained. Relatively homogenous means that a ratio between a maximum concentration N_E in a region to one of the first and second surfaces **101**, **102** and a minimum concentration N_M in the middle of the semiconductor body **100** is less than 200, less than 100, less than 50, or even less than 10, that is $N_E/N_M<200$, $N_E/N_M<100$, $N_E/N_M<50$, or even $N_E/N_M<10$. Referring to FIGS. **2** and **6**, the semiconductor body **100** may include two maxima (see, FIG. **2**), one in the region of each surface **101**, **102**, or only one maximum (see, FIG. **6**), namely in the region of one surface while the other maximum was removed by PDG. In case there are two maxima, N_E denotes the concentration of the greater one of the two maxima. The minimum "in the middle of the semiconductor body **100**" is the minimum spaced apart from those region affected by the PDG process. According to one embodiment, the minimum in the middle is distant more than 0.2d from each of the surfaces **101**, **102**. According to one embodiment, the minimum is in a region of between 0.3d and 0.7d from one of the first and second surfaces **101**, **102**, wherein d denotes the thickness of the semiconductor body **100**. If there is an optional thinning process, d denotes the thickness after the thinning process.

Although various exemplary embodiments of the invention have been disclosed, it will be apparent to those skilled in the art that various changes and modifications can be made which will achieve some of the advantages of the invention without departing from the spirit and scope of the invention. It will be obvious to those reasonably skilled in the art that other components performing the same functions may be suitably substituted. It should be mentioned that features explained with reference to a specific figure may be combined with features of other figures, even in those cases in which this has not explicitly been mentioned. Further, the methods of the invention may be achieved in either all software implementations, using the appropriate processor instructions, or in hybrid implementations that utilize a combination of hardware logic and software logic to achieve the same results. Such modifications to the inventive concept are intended to be covered by the appended claims.

Spatially relative terms such as "under," "below," "lower," "over," "upper" and the like, are used for ease of description to explain the positioning of one element relative to a second element. These terms are intended to encompass different orientations of the device in addition to different orientations than those depicted in the figures. Further, terms such as "first," "second" and the like, are also used to describe various elements, regions, sections, etc. and are also not intended to be limiting. Like terms refer to like elements throughout the description.

As used herein, the terms "having," "containing," "including," "comprising" and the like are open ended terms that indicate the presence of stated elements or features, but do not preclude additional elements or features. The articles "a," "an" and "the" are intended to include the plural as well as the singular, unless the context clearly indicates otherwise.

With the above range of variations and applications in mind, it should be understood that the present invention is not limited by the foregoing description, nor is it limited by the accompanying drawings. Instead, the present invention is limited only by the following claims and their legal equivalents.

What is claimed is:

1. A method, comprising:

implanting recombination center atoms via a first surface into a semiconductor body;

causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process;

forming a doped region in the semiconductor body adjacent one of the first surface and a second surface, wherein the second surface is opposite the first surface,

wherein the doped region is formed after implanting the recombination center atoms.

2. The method of claim **1**, wherein the recombination center atoms comprise noble metal atoms.

3. The method of claim **2**, wherein the recombination center atoms are selected from the group consisting of

platinum (Pt) atoms;

gold (Au) atoms; and

palladium (Pd).

4. The method of claim **1**, wherein implanting the recombination center atoms comprises implanting the recombination center atoms with an implantation dose of between 1E11 cm^{-2} and 1E14 cm^{-2}.

5. The method of claim **4**, wherein implanting the recombination center atoms comprises implanting the recombination center atoms with an implantation dose of between 5E11 cm^{-2} and 5E12 cm^{-2}.

6. The method of claim **1**, wherein the first diffusion process comprises heating the semiconductor body to a temperature of between 650° C. and 950° C. for a duration of between 1 hour and 2 hours.

7. The method of claim **1**, further comprising:

causing interstitials resulting from forming the doped region to diffuse in the semiconductor body away from the one of the first surface and the second surface in a second diffusion process.

8. The method of claim **7**, wherein the second diffusion process comprises heating the semiconductor body to a temperature of between 500° C. and a maximum of the temperature in the first diffusion process for a duration of between 1 hour and 2 hours.

9. The method of claim **1**, wherein forming the doped region comprises introducing dopant atoms into the one of the first and second surfaces, and melting those sections of the semiconductor body into which dopant atoms were introduced by a laser annealing process.

10. The method of claim 9, wherein the laser annealing process comprises forming an antireflective coating layer on the one of the first and second surfaces.

11. The method of claim 10, wherein the antireflective coating layer comprises at least one of silicon oxide and silicon nitride.

12. The method of claim 9, wherein introducing the dopant atoms comprises implanting the dopant atoms.

13. The method of claim 1, wherein forming the doped region comprises introducing dopant atoms into the one of the first and second surfaces, and annealing at least those sections of the semiconductor body into which dopant atoms were introduced by an RTA process.

14. The method of claim 13, wherein providing the dopant atoms comprises implanting the dopant atoms into the semiconductor via the one of the first surface and the second surface.

15. The method of claim 1, wherein implanting the recombination center atoms comprises implanting the recombination center atoms through a scattering layer.

16. The method of claim 15, wherein the scattering layer is an oxide layer on the first surface.

17. The method of claim 16, wherein the oxide layer comprises a thickness of between 10 nanometers and 20 nanometers.

18. The method of claim 1, wherein the semiconductor body comprises a basic doping of a first conductivity type, and wherein the doped region is a region of the first conductivity type.

19. The method of claim 18, wherein the first conductivity type is an n-type.

20. The method of claim 19, wherein the dopant region comprises phosphorous (P) atoms.

21. The method of claim 1, wherein implanting the recombination center atoms comprises implanting the recombination center atoms all over the first surface into the semiconductor body.

22. The method of claim 1, wherein implanting the recombination center atoms comprises implanting the recombination center atoms using an implantation mask which covers sections of the first surface and prevents recombination center atoms from being implanted into those sections of the first surface covered by the implantation mask.

23. The method of claim 1, wherein forming the recombination centers comprises forming recombination centers such that a maximum concentration of the recombination centers in a region adjoining one of the first surface and the second surface is below the solubility limit at the temperature of the first diffusion process.

24. The method of claim 1, wherein forming the recombination centers atoms comprises forming the recombination centers such that the concentration of the recombination centers in a region adjoining one of the first surface and the second surface is above the solubility limit at the temperature of the first diffusion process.

25. The method of claim 24, wherein the temperature of the first diffusion process is selected from a range of between 850° C. and 750° C., and wherein the implantation dose is selected from a range of between 3E12 cm^{-2} and 1E13 cm^{-2}.

26. A semiconductor device, comprising:
- a semiconductor body comprising a first surface and a second surface;
- recombination centers in a region between the first surface and the second surface,
- wherein a profile of the recombination centers in a vertical direction of the semiconductor body comprises a minimum spaced apart from each of the first and second surfaces and at least one maximum,
- wherein a ratio between the at least one maximum and the minimum is less than 200.

27. The semiconductor device of claim 26, wherein the ratio between the at least one maximum and the minimum is less than 100, less than 50, or less than 10.

28. The semiconductor device of claim 26, wherein the profile of the recombination centers in the vertical direction comprises only one maximum.

29. The semiconductor device of claim 26, wherein a distance between the minimum and each of the first and second surfaces is at least 0.2d, wherein d is the distance between the first surface and the second surface.

30. The semiconductor device of claim 26, wherein the recombination centers comprise noble metal atoms.

31. The semiconductor device of claim 26, wherein the at least one maximum is in a range of between 1E13 cm^{-3} and 1E16 cm^{-3}, and the minimum is in a range of between 5E11 cm^{-3} and 5E14 cm^{-3}.

32. The semiconductor device of claim 26, wherein the semiconductor device comprises:
- a base region of a first doping spaced apart from the first surface; and
- an emitter region of the first doping type adjoining the first surface and higher doped than the base region,
- wherein the recombination centers are at least arranged in the base region.

33. The semiconductor device of claim 32, wherein a doping concentration of the basic doping is selected from a range of between 1E12 cm^{-3} and 5E15 cm^{-3}.

34. The semiconductor device of claim 32, wherein a maximum doping concentration of the emitter region is selected from a range of between 1E19 cm^{-3} and 1E21 cm^{-3}.

35. A method, comprising:
- implanting recombination center atoms via a first surface into a semiconductor body; and
- causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process,
- wherein implanting the recombination center atoms comprises implanting the recombination center atoms through a scattering layer.

36. A method, comprising:
- implanting recombination center atoms via a first surface into a semiconductor body;
- causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process; and
- causing interstitials resulting from forming the doped region to diffuse in the semiconductor body away from the one of the first surface and the second surface in a second diffusion process.

37. A method, comprising:
- implanting recombination center atoms via a first surface into a semiconductor body; and
- causing the implanted recombination center atoms to diffuse in the semiconductor body in a first diffusion process;
- wherein forming the recombination centers comprises forming recombination centers such that a maximum concentration of the recombination centers in a region adjoining one of the first surface and the second surface is below the solubility limit at the temperature of the first diffusion process.

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